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RELATION OF THE WATER-RETAINING CAPACITY OF A SOIL TO ITS HYGROSCOPIC COEFFICIENT[1]

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INTRODUCTION

In recent years the importance of the water contained in the deeper portions of the subsoil—that below the depth penetrated by the roots of crop plants—has been a much-discussed question, and most extreme views are entertained, both as to its rôle in the moisture supply of annual crop plants in dry-land regions and as to its influence upon the indefinite maintenance of the mineral nutrients in the surface soil.

In a recent analysis of the outlook for the reclamation of nonirrigable lands in regions of very low rainfall, Hall (12)[2], while mentioning that some work in widely separated regions has cast doubt upon the common supposition that—

> the subsoil below the actual range of the roots of the crop may still return water by capillarity to the higher levels that are being depleted, the deeper subsoil thus acting as a kind of regulating reservoir absorbing rain in times of excess and returning it when the need arises—

has pointed out that—

> the evidence on either side is far from being conclusive and more experiment is very desirable (12, p. 641).

The present differences in views appear to be due to the failure in laboratory experiments and field studies to take into consideration some physical constant that is directly related to both the lower limit of available moisture and the water-retaining capacity of the soil, if we define the latter as the maximum amount which a soil will carry after it has been saturated and then, protected from both direct evaporation and the indirect effects of this as well as the action of plant roots, allowed to come into approximate moisture equilibrium by the downward movement of the excess of water into the subsoil mass. The lower limit of available moisture as

[1] The work reported in this paper was carried out in 1912–13 at the Nebraska Agricultural Experiment Station, where the authors were, respectively, Chemist and Research Assistant in Chemistry.

[2] Reference is made by number to "Literature cited," p. 70–71.

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determined by plant-house experiments, in which crop plants were grown in 6-foot cylinders and left unwatered until they matured or died of lack of water (2), appears to be practically coincident with the hygroscopic coefficient. Up to the present a method of estimating the water retentiveness in the field from one of the physical constants of the soil has not been developed. The laboratory experiments and field studies of the authors make it appear that, in the case of soils with hygroscopic coefficients between 14 and 3, this bears a rather simple relation to the hygroscopic coefficient, and that, in coarser soils, while it bears a much less simple relation, this is still one that may be experimentally determined. As the great majority of the tillable soils of dry-land regions fall within the limits of hygroscopicity mentioned, it would appear that, through the determination of the moisture content and the hygroscopic coefficient in the case of samples of the deeper subsoil, we could learn both the percentage of the physiologically important water and the departure of this from the maximum which the particular subsoil could retain.

The hygroscopic coefficient may be determined directly or more conveniently by one of the indirect methods that have been proposed (8, p. 73; 5, p. 410; 4, p. 531).

HISTORICAL REVIEW

The authors who maintain the theory "that water can rise to the surface from the deep layers by capillary action" are, as Rotmistrov has stated (23, p. 16), too numerous to name, but few of them offer any experimental evidence in support of the theory.

From field observations during unusually prolonged summer droughts Hall concluded that in certain soils the capillary rise of water might be as much as 200 feet (11, p. 94).

Mitscherlich, who has calculated the maximum possible elevation of water to be as high as 2 or 3 km. in heavy clays and loams (19, p. 192), considers this of no practical importance, on account of its extreme slowness of movement. From experiments with "the most varied soils" exposed for a 3-month period, during which they became appreciably altered by algæ, he observed no rise exceeding 0.8 meter and concluded that 1.5 meters from ground water may be regarded as the practical limit, so far as plants are concerned (20, p. 136).

In the case of one soil Tulaikow (24, p. 665) observed a rise of 135 cm. in 513 days, and the maximum had not yet been reached; while with three finer-textured soils the rise at the end of a year and a half had become stationary at 60 to 70 cm.

From field studies in Saskatchewan in 1904 and 1905 one of the authors concluded that in semiarid regions the roots go to the stored water in the subsoil instead of the latter being elevated to the surface foot by capillarity and that but comparatively little water which has once passed below the first foot is lost by evaporation (1, p. 42).

Leather (13, p. 105–106), from a study of the moisture in a fallow field at Pusa, India, during the dry season of 1906, concluded that—

during a dry period water moves upward toward the surface from a limited depth only; this limited depth increases with the period. Below this depth the water is stationary or possibly still draining downward.

In the Pusa soil he found the maximum distance that water moved upward during the period to be somewhat more than 3 feet and that eventually it was about 7 feet. While he did not determine the hygroscopicity of his soils or recognize in this a means of estimating the relative surfaces of the solid particles, he concluded that—

the relative water-retaining power of a soil after drainage has ceased is closely related to the total surface possessed by the solid particles, and it is probable that from a determination of the latter the water-holding capacity of soils may be ascertained.

Extreme views of the importance of the upward capillary movement have been expressed by Cameron (10) and McGee (16, 17). The former, mentioning that in humid areas the larger part of the water from rains returns to the surface, states that it sometimes does so "through distances of many feet" (10, p. 23). He assumes the upward capillary movement to be sufficient to bring to the surface annually more than sufficient potash and phosphoric acid to replace the amounts that would be removed by—

one ton per acre of dry crop containing one per cent. potash and 0.6 per cent. phosphoric acid (10, p. 77).

McGee has estimated that in the Great Plains of the United States the quantity of water which the deeper subsoil contributes to the growth of crops is not less than 6 inches annually and that by supplementing the local rainfall it suffices—

to render the land productive and habitable over a vast area which would otherwise be unproductive (17, p. 40); that it will move during the course of a year from a depth of say 10 feet; and that under favorable conditions of subsoil texture it will move during a term of years and progressively equalize the distribution of subsoil water through a depth of 30 or 35 feet (16, p. 11).

Widtsoe and McLaughlin (25, p. 230) have suggested the term "lento capillary point" to designate the moisture content of a soil at which capillary movements become very sluggish. They consider that it can not be defined with precision. In a field study of a soil very uniform in texture to a depth of 8 feet they found the moisture content to vary between about 10 and 18 per cent and the lento capillary point to lie between 12 and 13 per cent.

From experiments with crop plants grown in cylinders 6 feet deep, in which the hygroscopic coefficients of all the soils used were determined, one of the authors concluded that the stored moisture in the different depths of subsoil in the case of ordinary dry lands becomes available to

the plants by the roots being developed into these depths, but little water being elevated by capillarity from the zone below that traversed by the roots (2, p. 121).

Metal cylinders from 2 to 6 feet long and 4 inches in diameter were filled with a subsoil having a hygroscopic coefficient of 5.6, half with soil in a moister condition and half with it in a drier, allowed to stand for several months and then the change in moisture distribution determined. In most of the experiments the moisture content of the drier soil was approximately equal to the hygroscopic coefficient. When the water content of the moister soil was below about twice the hygroscopic coefficient, the capillary movement of water in any direction was slight; but when it was distinctly above this, there was a practically uniform movement from the moister into the drier soil (3, p. 286).

The work of Rotmistrov (23), near Odessa, covers a period of 15 years, 1895–1909. The ground water there lies at a depth of over a hundred feet and the soil is a Chernozem containing 3 to 5 per cent of organic matter. He assumes the "useless" (nonavailable) water at all depths in this soil to be about 10 per cent and attaches physiological importance to only the portion in excess of this. Moisture determinations, some 60,000 in all, were made at frequent intervals throughout the year at successive intervals of 5 or 10 cm., in some cases to a depth of 7 feet or more, both in clean fallows and under a great variety of crops. He found that when the subsoil is moist, the roots of annual crops penetrate to a depth of 2 to 5 feet and those of various perennials—alfalfa, trees, and shrubs—sometimes as deep as 60 feet. On the old plowed fields he found a permanently moist layer of subsoil extending from 4½ or 5½ feet to the water table, while on waste land occupied by weeds, etc., the permanently moist layer was encountered first at 14 to 30 feet. Above this is, first, a layer of subsoil which becomes moist or dry according to whether it is in fallow or crop, and, lastly, overlying the latter is the surface layer, varying from less than 2 to as much as 5 feet, which in every year becomes moist. He concludes that water percolating beyond a depth of 16 to 20 inches does not return to the surface except by way of the roots, the portion escaping the roots going down into the deeper layers at the rate of about 7 feet yearly.

Using glass tubes and wooden boxes, he carried out experiments with soil from the experimental field. Placing these in water, he observed a rise of less than 3 feet in three months. As the movement is so slow in the soil with water less than 3 feet below the surface, he concludes it will not move at all in the field where it is at a depth of over 100 feet.

Burr (9), from a 7-year study (1907 to 1913) of the total moisture in the first 3 to 15 feet of the comparatively uniform loessial soil on the table-land at North Platte, Nebr., where the water table is at a depth of over 200 feet, concludes that there is little upward movement of subsoil water, and that—

water supply by capillarity is not an important factor in crop production on Nebraska upland soils (9, p. 10).

The hygroscopic coefficients of the soil samples were not determined, but the mechanical analyses of eight sets of samples from the first 3 feet permit a calculation of these values by the Briggs and Shantz formula (8, p. 73); these vary from 6.1 to 8.5. From the extremes of moisture found he considers 16 to 18 per cent the maximum amount of water the soil can retain against gravity, and 7 to 8 per cent its minimum point of available water (9, p. 18–19). From this it appears that on that type of soil the hygroscopic coefficient is approximately the lower limit of available moisture, and that the maximum water content when downward movement ceases lies between 1.8 and 2.6 times the hygroscopic coefficient, if it is assumed that all the soil samples taken are sufficiently similar to justify such a comparison. This is in accord with our findings reported below.

CHARACTER OF SOILS USED

The soils were selected to represent some of the most important types of Nebraska, especially those of loessial origin, and not the whole range in texture from coarse sands with a hygroscopic coefficient less than 0.5 to clays with one in excess of 20. They include (Table I) six silt loams derived from the loess, five loams of residual origin, and one dune sand. Soil D is surface soil, Marshall silt loam, from the Experiment Station farm at Lincoln, and A the corresponding subsoil, taken from the third to the fifth foot. E and H similarly represent the surface soil and subsoil of the substation farm at Culbertson, and C and G corresponding depths of a prairie near McCook, both on Colby silt loam. Soils I, J, K, L, and M are from areas of residual soil mapped by the United States Bureau of Soils as belonging to the Sidney series (22, p. 58). I and K are surface soil and subsoil from a loam near Imperial, and M and L from a sandy loam near the same place. Soil J is a subsoil from the silt loam near Madrid, part of a bulk sample on which various studies (2, p. 46; 3, p. 249) have previously been reported. K and L are from the same depths as A, H, and G—viz, 3 to 5 feet—while J was from the fourth to the sixth foot.

Soil Q is a dune sand taken from a "blow-out" near Dunning, and is typical of the subsoil of the very extensive sand-hill region.

Soil B, the only soil from outside Nebraska included in the study, is from the Sulphur Spring Valley Dry-Land Experimental Farm, north of Douglas, Ariz. This was included because of its interesting conduct in the field. It was taken from the surface of a field which after two years of clean summer fallow, without bearing any crop at all, was found to contain no available water to a depth of 2 feet.

According to Ramann (21, p. 343),—

it is to be assumed that the capillary elevation of water is much more active in loess soils than with any other kind of soil.—Translation.

Six of the above soils are loess.

In Table I are reported the hygroscopic coefficient, the moisture equivalent (7, p. 140), the maximum water capacity as determined by the Hilgard method, and the total nitrogen.

TABLE I.—*Properties of soils used in the experiments*

Soil.	Total nitrogen.	Hygroscopic coefficient.	Moisture equivalent.	Ratio of moisture equivalent to hygroscopic coefficient.	Maximum water capacity.
Loess soil from near Lincoln:	*Per ct.*				*Per ct.*
Surface D	0. 244	10. 2	27. 8	2. 73	60. 9
Subsoil A	. 049	13. 3	29. 5	2. 22	65. 7
Loess soil from near McCook:					
Surface C	. 104	10. 5	24. 1	2. 30	63. 7
Subsoil G	. 029	8. 2	21. 2	2. 59	55. 4
Loess soil from near Culbertson:					
Surface E	. 079	10. 1	22. 5	2. 23	56. 8
Subsoil H	. 018	7. 6	19. 7	2. 59	57. 2
"Hard land" (residual) from near Imperial:					
Surface I	. 106	7. 1	16. 8	2. 37	53. 4
Subsoil K	. 016	3. 4	7. 5	2. 21	36. 0
"Sandy land" (residual) from near Imperial:					
Surface M	. 077	3. 3	7. 9	2. 39	34. 2
Subsoil L	. 023	3. 4	7. 2	2. 12	31. 0
"Hard land" from near Madrid:					
Subsoil J	. 021	5. 6	13. 5	2. 41	46. 3
Dune sand from Dunning:					
Subsoil Q	. 008	0. 6			25. 8
Arizona soil:					
Surface B	. 088	12. 9	25. 8	2. 00	60. 3

METHOD OF FILLING AND OPENING CYLINDERS

In bringing a soil to the desired moisture content we placed a weighed quantity of the air-dried soil, of which the moisture content had previously been determined, upon a large sheet of oilcloth on the floor of the mixing room, and, while the mass was being shoveled over, added the calculated amount of water in small portions. The whole mass was then mixed thoroughly, first by shoveling, then by passing it twice through a swinging sieve of ¼-inch mesh, and finally by again shoveling; then it was immediately placed in a large covered can, allowed to stand for several days, again passed through the swinging sieve, returned to the can, and kept in this until transferred to the cylinders. The percentage of moisture thus secured was in the majority of cases from one-tenth to one-third higher than the hygroscopic coefficient, in the others it being nearer the desired amount.

In filling the cylinders the soil was added very slowly with constant tamping, care being taken to insure the firmness of that already in before adding more. Blows as uniform as possible were delivered by means of a tamper, for which we used a 2-inch rubber stopper on the end of a ⅜-inch gas pipe 3 feet long. As the cylinders were being filled, three samples of each soil were taken for moisture determinations.

In such experiments as these the removal of exactly the desired depth of soil is an important operation, but in many cases a difficult one. Our practice with those of the metal cylinders in which there was no direct contact of the soil column under experiment with the subsoil mass was to place a cylinder on a table, and, by means of a can opener, to open it lengthwise, 6 to 12 inches at a time. The measured portions of the column of soil were then sliced off by means of a large spatula and placed in Mason jars, which were covered at once. With those of the cylinders open at the bottom and having the soil column in contact with the subsoil mass the successive layers were removed by a plate auger whose diameter was a little less than that of the cylinders. After the main portion of each section had been thus removed, the small residue next the cylinder wall was taken up with a spoonlike instrument. After all the samples had been secured from a cylinder, the contents of each jar were thoroughly mixed. The moisture determinations were made in an oven kept at 110° C., through which passed a rapid current of dry air. Precautions were taken to insure the thorough drying of all the samples.[1]

As was to be expected, all the surface soils, after being tamped into the cylinders, much resembled their condition in a well-prepared seed bed. The structure of the subsoils, with the exception of A, very closely resembled that found in excavations in the field. In the cylinders soil A had in all cases a granular structure, very different from that observed in the field. This, however, did not appear to influence seriously the movement of moisture, as will be seen below in the comparison of field data with those obtained in the laboratory experiments.

In most of the experiments duplicate cylinders were employed. The moisture conditions in the duplicates are so similar in all the soils, except the sand, Q, that we report only the average, no purpose being served by reporting the data from the two separately. With the sand the data on all the cylinders are reported. As illustrations of the degree of concordance with the soils other than the sand the data on two, C and I, are given in Table II.

The results in these experiments and in those previously reported (3) would make it appear an unprofitable expenditure of time, at least in preliminary studies, to use duplicate cylinders.

[1] Further particulars of the method have already been given in a report on cylinder experiments (2, p. 29).

TABLE II.—*Moisture conditions found on opening two typical pairs of duplicate cylinders, showing concordance of duplicates in the case of the finer-textured soils*

Depth of section.	Soil C.			Soil I.		
	Cylinder I.	Cylinder II.	Average.	Cylinder I.	Cylinder II.	Average.
Inches.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
1	23.2	23.7	23.4	7.8	7.9	7.8
2	21.7	22.6	22.1	7.3	7.6	7.4
3	21.1	21.4	21.2	7.1	7.1	7.1
4	20.4	20.3	20.3	6.8	6.4	6.6
5	19.9	20.5	20.2	6.5	6.4	6.4
6	19.7	20.1	19.9	6.3	6.1	6.2
7	19.1	19.7	19.4	6.0	5.9	5.9
8	18.9	19.2	19.0	5.7	5.5	5.6
9	17.6	18.7	18.1	5.6	5.0	5.3
10	17.1	17.8	17.4	5.4	5.0	5.2
11	16.6	17.0	16.8	5.2	4.9	5.0
12	15.2	15.7	15.4	4.9	4.8	4.8
13	14.0	15.0	14.5	4.8	4.7	4.7
14	13.0	13.1	13.0	4.9	4.7	4.8
15	12.8	13.0	12.9	4.7	4.6	4.6
16	12.6	12.8	12.7	4.8	4.5	4.6
17	12.4	12.5	12.4	4.8	4.4	4.6
18	12.0	12.7	12.3	4.8	4.4	4.6
19	12.4	12.5	12.4	4.8	4.4	4.6
20	12.3	12.6	12.4	4.8	4.5	4.6
21	12.3	12.6	12.4	4.9	4.6	4.7
22	12.3	12.3	12.3	4.8	4.6	4.7
23	12.5	11.8	12.1	4.7	4.7	4.7
24	12.5	12.1	12.2	4.6	4.7	4.6
Average	15.9	16.3	16.1	5.5	5.3	5.4

FINAL WATER CONTENT WHEN SOIL COLUMN IS IN CAPILLARY CONNECTION WITH THE NATURAL SUBSOIL AND FULLY PROTECTED FROM EVAPORATION

A.—WITH A UNIFORM LOAM.—During the latter part of March, 1913, four cylinders 3 feet long, 6 inches in diameter, and open at both ends were placed in holes 8 inches in diameter bored in the loess floor of a greenhouse. The open space surrounding each cylinder was packed very tightly with moist subsoil in order to hold it firmly in place. The air-dried soil, J, was filled into the cylinders to a depth of 30 inches, thus bringing it to within 6 inches of the top, tamping it as above described (p. 33). Thus, direct capillary connection could be established between the soil of the cylinders and the natural subsoil, a loess with a hygroscopic coefficient of about 13. The moisture condition of the latter at a depth of 3 feet was similar to that in the fields near by. On the surface of the tamped soil a 2-inch layer of gravel was placed and 15 pounds of water added as rapidly as it soaked away, about 15 hours being required. As soon as all the water had been added, the tops of the cylinders were closed with tightly fitting covers; and a layer of moist soil, 8 inches in depth, was placed over all to prevent any loss by evaporation and also to protect the tops of the soil columns from the high temperature prevailing in the

greenhouse during the middle of the day (1, p. 26). As the weight of the air-dried soil in each cylinder was approximately 50 pounds, the added water was sufficient to have raised the moisture content to over 30 per cent if no seepage had occurred. During July, after the cylinders had been allowed 96 days in which to lose water by seepage, Cylinder IV was opened and the moisture content determined in the successive inch sections. The three others were opened at intervals of 8, 5, and 17 days, respectively. As the moisture content was no lower in the last three than in the first it would appear that equilibrium had been practically established by the time the first was opened. In Table III are reported the data on these as well as those on three cylinders (No. I to III) which, in an earlier experiment,[1] had been filled with the same soil and had been similarly treated (3, p. 280).

TABLE III.—*Ratio of water content to hygroscopic coefficient in soil J, entirely protected from evaporation, but in capillary connection with the earth's soil mass. To the cylinders, each filled with approximately 50 pounds of air-dried soil, there was added 15 pounds of water, after which they were left from 31 to 126 days*

Depth of section.	Cylinder No.							
	I (31 days).	II (44 days).	III (54 days).	IV (96 days).	V (104 days).	VI (109 days).	VII (126 days).	IV-VII (average 109 days).
Inches.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
1	3.1	3.3	3.1	2.5	3.0	2.6	2.6	2.6
2	3.1	3.2	3.0	2.4	2.8	2.6	2.5	2.6
3	3.1	3.2	3.1	2.3	2.7	2.5	2.5	2.5
4	3.2	3.2	3.1	2.4	2.6	2.5	2.5	2.5
5	3.3	3.2	3.1	2.4	2.6	2.5	2.5	2.5
6	3.2	......	3.1	2.4	2.6	2.6	2.4	2.5
7	3.2	3.2	3.1	2.4	2.6	2.6	2.4	2.5
8	3.3	3.3	3.2	2.4	2.5	2.5	2.4	2.5
9	3.4	3.4	3.3	2.4	2.6	2.4	2.4	2.5
10	3.3	3.4	3.3	2.5	2.6	2.4	2.4	2.5
11	3.2	3.5	3.4	2.4	2.6	2.5	2.3	2.4
12	3.5	3.4	3.3	2.4	2.6	2.5	2.5	2.5
13	3.6	3.4	......	2.4	2.6	2.5	2.4	2.5
14	3.6	3.5	3.4	2.4	2.6	2.4	2.4	2.5
15	3.7	3.6	3.4	2.4	2.5	2.4	2.5	2.5
16	3.6	3.4	3.5	2.3	2.5	2.4	2.6	2.4
17	3.7	3.6	3.5	2.3	2.5	2.4	2.5	2.4
18	3.7	3.9	3.5	2.3	2.6	2.4	2.5	2.4
19	3.7	3.7	3.5	2.3	2.6	2.4	2.5	2.4
20	3.7	3.7	3.6	2.4	2.6	2.4	2.5	2.5
21	3.8	3.8	3.7	2.3	2.5	2.3	2.5	2.4
22	4.0	4.1	3.8	2.3	2.6	2.4	2.5	2.4
23	4.2	3.9	3.8	2.3	2.5	2.4	2.4	2.4
24	4.2	3.9	3.8	2.3	2.5	2.5	2.5	2.4
25	4.2	3.9	4.1	2.3	2.5	2.5	2.5	2.4
26	4.4	4.3	4.2	2.3	2.5	2.5	2.5	2.4
27	4.5	4.5	4.2	2.3	2.5	2.5	2.5	2.4
28	4.5	4.3	4.2	2.5	2.4	2.5	2.4	2.5
29	4.6	4.3	4.5	2.5	2.5	2.5	2.4	2.5
30	4.8	4.3	4.6	2.5	2.5	2.5	2.5	2.5
Average	3.7	3.7	3.6	2.4	2.6	2.5	2.5	2.5

[1] The various experiments are reported in what appears a logical order for purposes of discussion rather than in the order in which they were performed.

In the latter group, exposed a year before, equilibrium had not been attained when the cylinders had been opened after periods of 31, 44, and 54 days, respectively, and the moisture content increased with the depth; while in the latter experiment, with a considerably longer exposure, the water was quite uniformly distributed throughout the 30 inches, varying only between 13.5 and 14.0, except in the first 2-inch section, in which it averaged 14.5 per cent.

The final average of the moisture content of the four cylinders of the later group (No. IV to VII) was 13.8, between 2.4 and 2.5 times the hygroscopic coefficient and approximately the same as the moisture equivalent, 13.5.

TABLE IV.—*Ratio of moisture content to hygroscopic coefficient in soil J, entirely protected from evaporation and separated from the earth's soil mass by a 6-inch layer of coarse quartz sand or gravel. To the cylinders, filled with approximately 50 pounds of air-dried soil, there was added 15 pounds of water, after which the cylinders were left 126 days*

Depth of section.	With sand.		With gravel.		Average, I-IV.
	Cylinder I.	Cylinder II.	Cylinder III.	Cylinder IV.	
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	3.7	3.4	3.4	3.3	3.4
2	3.5	3.2	3.2	3.0	3.2
3	3.4	3.1	3.2	3.0	3.2
4	3.4	3.1	3.2	3.0	3.2
5	3.5	3.2	3.0	2.9	3.1
6	3.5	3.2	3.2	3.0	3.2
7	3.5	3.2	3.3	3.1	3.3
8	3.6	3.2	3.3	3.2	3.3
9	3.7	3.3	3.4	3.1	3.4
10	3.7	3.3	3.4	3.1	3.4
11	3.7	3.3	3.4	3.2	3.4
12	3.7	3.4	3.5	3.2	3.4
13	3.8	3.4	3.5	3.2	3.5
14	3.8	3.5	3.6	3.3	3.5
15	3.9	3.5	3.6	3.3	3.6
16	3.9	3.6	3.7	3.4	3.6
17	4.1	3.6	3.7	3.5	3.7
18	4.0	3.7	3.8	3.4	3.7
19	4.1	3.7	3.9	3.5	3.8
20	4.1	3.8	3.9	3.5	3.8
21	4.2	3.8	3.9	3.6	3.9
22	4.3	3.9	3.9	3.6	3.9
23	4.5	3.9	4.1	3.6	4.0
24	4.6	4.0	4.1	3.7	4.1
25	4.8	4.1	4.2	3.7	4.2
26	4.9	4.2	4.2	3.7	4.3
27	4.9	4.2	4.3	3.8	4.3
28	5.4	4.5	4.6	3.9	4.6
Average	4.0	3.6	3.7	3.3	3.6

B.—WITH A LOAM INTERRUPTED BY A GRAVEL OR SAND LAYER.—To determine the effect of an interrupting layer of coarse material, sand or gravel, four similar cylinders were filled with the same soil, J, but on the loess at the bottom of each cylinder there was first placed a 6-inch layer of quartz sand in the case of Cylinders I and II; and of gravel in III and IV. These coarse materials were tamped in uniformly, after which the

soil was added as above described and the same amount of water, 15 pounds, added. All four were opened at the end of 126 days. The moisture conditions are shown in Table IV. The moisture content was much higher, over 6 per cent on the average, than in the cylinders having no layer of coarse material. Further, in those with the sand or gravel the moisture in the soil column was not uniformly distributed, being about 6 per cent higher, just above the coarse layer, than near the surface. Neither the sand nor the gravel used in this experiment was as coarse as much of the material found naturally underlying arable soils.

C.—WITH LAYERS OF SIX DIFFERENT SOILS VARIOUSLY ARRANGED.—In this experiment we used soils selected to exhibit a wide range in hygroscopicity while still confining the set to soils representing important Nebraska types. These were placed in seven metal cylinders, open at both ends, 18 inches long, and 6 inches in diameter. The cylinders had been placed in a trench, 2 feet deep, dug in the loess floor of the greenhouse. In the case of each the sharp edge of the lower end of the cylinder was driven into the bottom of the trench to a depth of 2 inches. Then each cylinder was filled, in 2-inch layers, with six different soils, the layers being arranged differently in each (Table V). Thus, direct capillary connection was established between the natural subsoil and the soil column. Each soil in an air-dry condition was filled into the cylinder as above described. After the whole of the layer had been tamped in a small square piece of ¼-inch mesh galvanized-wire screen was placed on the surface before beginning the addition of the next layer, so that the dividing surfaces between the different layers of soil might be more readily recognized on opening the cylinders.

In the arrangement of the soils in Cylinders II to VII each soil appears once at the top, once at the bottom, and once in each intermediate position. In No. I the soils are arranged from top to bottom in the order of their hygroscopic coefficients, the soil with the lowest being at the top, while in No. VII the order is reversed.

TABLE V.—*Arrangement of soil layers in the different cylinders, showing the soils used, their hygroscopic coefficients, and their moisture equivalents* [a]

SOILS

Depth.	Cylinder No.						
	I.	II.	III.	IV.	V.	VI.	VII.
Inches.							
1–2	Q	Q	L	J	H	D	A
3–4	L	A	Q	L	J	H	D
5–6	J	D	A	Q	L	J	H
7–8	H	H	D	A	Q	L	J
9–10	D	J	H	D	A	Q	L
11–12	A	L	J	H	D	A	Q

[a] The heavy lines indicate the position of the sand layers.

TABLE V.—*Arrangement of soil layers in the different cylinders, showing the soils used, their hygroscopic coefficients, and their moisture equivalents*—Continued

Depth.	Cylinder No.						
	I.	II.	III.	IV.	V.	VI.	VII.
HYGROSCOPIC COEFFICIENT							
Inches.							
1–2	0.6	0.6	3.4	5.6	7.6	10.2	13.3
3–4	3.4	13.3	0.6	3.4	5.6	7.6	10.2
5–6	5.6	10.2	13.3	0.6	3.4	5.6	7.6
7–8	7.6	7.6	10.2	13.3	0.6	3.4	5.6
9–10	10.2	5.6	7.6	10.2	13.3	0.6	3.4
11–12	13.3	3.4	5.6	7.6	10.2	13.3	0.6
MOISTURE EQUIVALENT							
1–2	1.5	1.5	7.2	13.5	19.7	27.8	29.5
3–4	7.2	29.5	1.5	7.2	13.5	19.7	27.8
5–6	13.5	27.8	29.5	1.5	7.2	13.5	19.7
7–8	19.7	19.7	27.8	29.5	1.5	7.2	13.5
9–10	27.8	13.5	19.7	27.8	29.5	1.5	7.2
11–12	29.5	7.2	13.5	19.7	27.8	29.5	1.5

After placing in the cylinder the six layers as described we added a 2-inch layer of gravel to the top of the column and then applied 7 pounds of water. As the soil column in each cylinder weighed not more than 15 pounds, this amount of water was sufficient to insure saturation, as it would have raised the moisture content to 50 per cent or more if the soil could have retained so much. As soon as all the water had been added, the tops of the cylinders were closed with tightly fitting covers and, as in sections A and B, a layer of moist soil was placed over all in order to prevent any evaporation and to protect the cylinders from the heat of the sun.

The cylinders, filled on September 7, 1912, were allowed to remain undisturbed for 69 days, when they were removed from the trench and opened, placing each on its side, cutting the metal from top to bottom and flattening out the metal sheet, thus exposing the whole soil column to observation. Each layer was carefully detached by means of a spatula, freed of all material belonging to the layers above and below, and thoroughly mixed for the moisture determination. The moisture conditions found on opening the cylinders are shown in the accompanying tables, VI giving the percentages of total water, VII that of free water, VIII the ratio of the total water to the hygroscopic coefficient, and IX the ratio of the total water to the moisture equivalent. The

term "free water" is used to designate the difference between the total water and the hygroscopic coefficient (14, p. 66) and is not synonymous

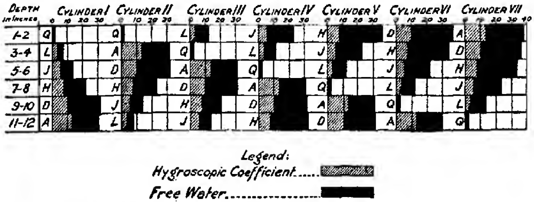

Fig. 1.—Diagram showing the relation of the percentage of water retained to the hygroscopic coefficient and the influence of an interrupting layer of coarse sand (soil Q). The seven soil columns, consisting of 2-inch layers of six different soils variously arranged, were saturated and then allowed to stand for 69 days protected from evaporation and in contact with the natural subsoil mass.

with "gravitational water" as it is employed by some (15, p. 207). The data are presented graphically in figure 1.

Table VI.—*Total water in the successive soil layers* [a]

Depth.	Cylinder No.						
	I.	II.	III.	IV.	V.	VI.	VII.
Inches.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
1-2	2.2	2.2	12.2	22.9	36.0	37.6	38.3
3-4	7.7	31.5	2.4	11.2	22.6	34.2	36.0
5-6	13.4	31.9	30.8	2.5	12.4	22.1	33.9
7-8	22.2	23.1	31.6	30.6	2.4	12.1	23.7
9-10	31.8	13.8	19.8	31.8	30.1	2.3	13.4
11-12	30.4	7.7	13.4	23.2	31.2	29.5	2.7

[a] The heavy lines indicate the position of the sand layers.

Table VII.—*Free water in the successive soil layers*

Depth.	Cylinder No.						
	I.	II.	III.	IV.	V.	VI.	VII.
Inches.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
1-2	1.7	1.7	8.8	17.3	28.4	27.4	25.0
3-4	4.3	18.2	1.9	7.8	17.0	26.6	25.8
5-6	7.8	21.7	17.7	2.0	9.0	16.5	26.3
7-8	14.6	15.5	21.4	17.3	1.9	8.7	18.1
9-10	21.6	8.2	12.2	21.6	16.8	1.8	10.0
11-12	17.1	4.3	7.8	15.6	21.0	16.2	2.1

TABLE VIII.—*Ratio of water content to hygroscopic coefficient in the successive soil layers*[a]

A.—DATA ARRANGED ACCORDING TO DEPTH

Depth.	Cylinder No.						
	I.	II.	III.	IV.	V.	VI.	VII.
Inches.							
1-2	4.4	4.4	3.6	4.1	4.7	3.7	2.9
3-4	2.1	2.4	4.8	3.3	4.0	4.5	3.5
5-6	2.4	3.1	2.3	5.0	3.6	4.0	4.5
7-8	2.9	3.0	3.1	2.3	4.8	3.5	4.2
9-10	3.1	2.5	2.6	3.1	2.3	4.6	3.9
11-12	2.3	2.1	2.4	3.1	3.1	2.2	5.4

B.—DATA ARRANGED ACCORDING TO SOILS

Soil No.	Cylinder No.						
	I.	II.	III.	IV.	V.	VI.	VII.
Q	4.4	4.4	4.8	5.0	4.8	4.6	5.4
L	2.1	2.1	3.6	3.3	3.6	3.5	3.9
J	2.4	2.5	2.4	4.1	4.0	4.0	4.2
H	2.9	3.0	2.6	3.1	4.7	4.5	4.5
D	3.1	3.1	3.1	3.1	3.1	3.7	3.5
A	2.3	2.4	2.3	2.3	2.3	2.2	2.9

[a] The heavy lines indicate the position of the sand layers.

TABLE IX.—*Ratio of water content to the moisture equivalent in the successive soil layers*[a]

A.—DATA ARRANGED ACCORDING TO DEPTH

Depth.	Cylinder No.						
	I.	II.	III.	IV.	V.	VI.	VII.
Inches.							
1-2	1.5	1.5	1.7	1.7	1.8	1.3	1.3
3-4	1.1	1.1	1.6	1.6	1.7	1.7	1.3
5-6	1.0	1.1	1.0	1.7	1.7	1.6	1.7
7-8	1.1	1.2	1.1	1.0	1.6	1.7	1.8
9-10	1.1	1.0	1.0	1.1	1.0	1.5	1.9
11-12	1.0	1.1	1.0	1.1	1.1	1.0	1.8

B.—DATA ARRANGED ACCORDING TO SOILS

Soil No.	Cylinder No.						
	I.	II.	III.	IV.	V.	VI.	VII.
Q	1.5	1.5	1.6	1.7	1.6	1.5	1.8
L	1.1	1.1	1.7	1.6	1.7	1.7	1.9
J	1.0	1.0	1.0	1.7	1.7	1.6	1.8
H	1.1	1.2	1.0	1.1	1.8	1.7	1.7
D	1.1	1.1	1.1	1.1	1.1	1.3	1.3
A	1.0	1.1	1.0	1.0	1.0	1.0	1.3

[a] The heavy lines indicate the position of the sand layers.

The ratio of the total water to the hygroscopic coefficient is strikingly similar for all the soils where the sand layer did not interrupt their connection with the natural subsoil mass, it varying only from 2.1 to 3.1. For soil J it is similar to that found in section A above.

From the tables it will be seen that while it apparently makes no difference as to the order of the soil layers, with the exception of the dune sand Q, the interposition of this has in all cases greatly increased the amount of water held by the soils in the layers above it. The ratio of the total water to hygroscopic coefficient varies from 4.4 to 5.4 for the sand. Soil L shows a ratio of 2.1 in Cylinders I and II when below the sand, but of 3.3 to 3.9 in the others, where the sand underlies it. The ratios for J are 2.4 to 2.5 against 4.0 to 4.2, for H 2.6 to 3.1 against 4.5 to 4.7, for D 3.1 against 3.5 to 3.7, and for A 2.2 to 2.4 against 2.9. Thus, where the sand layer overlies the finer-textured soil the ratio of the retained moisture in the latter to the hygroscopic coefficient varies only between 2.1 and 3.1, while where it underlies the latter the ratio is from 0.4 to 2.1 higher.

The concordance of the retained moisture with the moisture equivalent (Table IX) where the sand layer does not interrupt is even much closer than its relation to the hygroscopic coefficient, the ratio being 1.0 to 1.2.

The sand layer Q is in all cases low in moisture compared with the amount found when water has been added to the surface of a 2-foot column of the same soil, it varying from 2.2 to 2.7 per cent; whereas in the latter it lies between 3.4 and 6.0 per cent, even 83 days after 1 inch of water has been added (p. 54).

Mitscherlich (20, p. 143) has pointed out that a very thin layer of loam in a sandy subsoil may markedly retard the movement of water through the latter. It is evident from the above that, conversely, thin layers of coarse sand or gravel may retard the movement of water in a loam.

FINAL WATER CONTENT WHEN DIFFERENT AMOUNTS OF WATER ARE ADDED TO THE TOP OF A COLUMN OF AIR-DRIED SOIL

In this experiment we used 8 pairs of cylinders, each 18 inches long, 6 inches in diameter, closed at the bottom, and provided with a tightly fitting cover. Twelve inches of air-dried soil D, containing 3.0 per cent of water, was tamped into each of 10, and a volume of water, equivalent to 1, 2, 3, 4, and 5 inches of rain, respectively, was added in small portions as rapidly as it was absorbed. The 6 other cylinders were similarly filled with the soil J in an air-dry condition, carrying 2.3 per cent of water, and treated with 1, 2, and 3 inches of water. Then the surface was covered with an inch layer of gravel, the cylinders covered, placed in a covered pit, and left undisturbed for 47 days, at the end of which they were opened, and the water determined in inch sections. The data

on the ratio of moisture content to the hygroscopic coefficient are reported in Table X.

TABLE X.—*Ratio of moisture content to hygroscopic coefficient in cylinders 47 days after 1 to 5 inches of water had been applied to the surface of columns of air-dried soil. The hygroscopic coefficient of soil D was 10.2 and of J 5.6, and the initial moisture content 3 and 2.3 per cent, respectively*

Depth.	Soil D.					Soil J.		
	1 in.	2 in.	3 in.	4 in.	5 in.	1 in.	2 in.	3 in.
Inches.								
1	1.9	2.7	3.0	3.7	.....	1.9	2.7	4.0
2	1.9	2.6	2.8	3.3	3.9	1.8	2.6	3.7
3	1.7	2.6	2.7	3.2	3.9	1.8	2.5	3.6
4	1.1	2.6	2.7	3.2	3.8	1.8	2.5	3.6
5	.8	2.4	2.7	3.2	3.8	1.7	2.4	3.5
6	.7	2.4	2.7	3.1	3.7	1.6	2.3	3.5
7	.6	1.8	2.6	3.1	3.6	1.3	2.3	3.5
8	.6	1.1	2.5	3.0	3.6	1.0	2.2	3.4
9	.5	.8	2.3	3.0	3.5	.9	2.1	3.1
10	.5	.7	2.0	2.9	3.5	.8	2.0	2.9
11	.5	.7	1.4	2.7	3.5	.8	2.0	2.8
12	.5	.7	1.2	2.6	3.5	.7	2.0	2.9

In all the cylinders the moisture content of all portions of the soil column had been raised either by capillary movement or by the passage of water vapor through the air. With soil D, capillary movement had affected the water content to a depth of 4 inches with 1 inch of water, to 8 inches with 2, and to 12 inches with 3, while with the still larger amounts the soil had become very moist throughout the whole length of the column. With soil J, where 1 inch of water had been added, the moisture was distributed uniformly to a depth of 4 or 5 inches, below which it decreased very rapidly; but, where twice as much had been added, the moistened soil extended to the bottom of the column; and with 3 inches the whole column had become very moist.

With the larger quantities of water, 4 and 5 inches with soil D and 3 inches with J, the downward movement had been arrested by the bottom of the cylinder; but the exposure was not sufficiently long to permit the moisture distribution to attain equilibrium.

FINAL WATER CONTENT WHEN TOP OF SOIL COLUMN IS EXPOSED TO EVAPORATION

Two water-tight cylinders, 6 inches in diameter, 3 feet deep, and closed at the bottom, were sunk in holes in the greenhouse, as described above; but the tops of the cylinders were placed level with the surface of the greenhouse floor and left open. On March 8, 1912, these cylinders, after being used in a similar experiment, previously reported (3, p. 283),

were refilled with soil J, carrying 15.2 per cent of water, and allowed to stand for 185 days before opening. The soil was tamped in as usual, this being continued to the top in the case of one and to within 1 inch of the top in the case of the other, the last inch in which was filled with air-dry soil. This, not being tamped, formed a shallow mulch. Both cylinders were so situated that the sun could shine on them nearly all day long; but, as whitewash was used on the windows, the maximum daily temperatures were not much higher than those in the open air. Thus, the mean maximum temperature in the plant house from July 5 to the end of the month was 93° F., while that in the open air was 91°. The corresponding average daily mean temperatures for the same period were 84° and 79°, respectively. For the month of August the mean maximum temperature in the plant house was 84° and in the open air 75°. While in the greenhouse the temperatures were somewhat higher, there was much less wind movement; and accordingly the soil in the cylinders was exposed to somewhat the same, or slightly less, drying influences that it would have experienced had it been in the open air but entirely protected from rainfall.

During the first three months of the experiment the cylinder with the compact surface was daily examined for the presence of minute cracks, and both cylinders were examined for the presence of crevices around the walls. As soon as cracks or crevices appeared they were filled with dry soil from the surface, so that all water lost would have to pass through the surface layer, instead of part of it escaping through such ventilating fissures. As, long before the experiment was concluded, cracks and crevices had ceased to form, examinations were made much less frequently after the third month.

The distribution of moisture found at the end of six months is shown in Table XI. The loss of water was greatest at the surface and least toward the bottom of the cylinders. All portions had suffered a loss of 4 per cent or more. A uniform upward movement, similar to that mentioned in the case of the earlier experiments, is to be observed in the case of the portion below the first 12 inches. The soil below this depth became as dry as in the earlier experiment (Table XII), but the latter had been exposed less than half as long. It is probable that the lower portion of the soil in both experiments had practically ceased to lose water. The loss of water from the two cylinders was similar, averaging for each 5.7 per cent. The final moisture content of the portion of the column below the twelfth inch varied only from 10 per cent at the top to 11 at the bottom, with an average of 10.7, or 1.9 times the hygroscopic coefficient.

TABLE XI.—*Loss of water from a uniform soil, J, protected from all loss at the sides and below, but fully exposed to evaporation at the surface. Both cylinders were filled on March 8 with soil containing 15.2 per cent of water and left for 185 days*

Depth of section.	Water content on opening cylinder.			Loss of water in 185 days.		
	Cylinder I, surface mulched.	Cylinder II, surface compact.	Average.	Cylinder I, surface mulched.	Cylinder II, surface compact.	Average.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	3.7	3.7	3.7	11.5	11.5	11.5
2	4.5	3.8	4.2	10.7	11.4	11.1
3	5.8	5.9	5.9	9.4	9.3	9.4
4	6.9	6.8	6.9	8.3	8.4	8.4
5	7.3	7.7	7.5	7.9	7.5	7.7
6	7.8	7.7	7.8	7.4	7.5	7.5
7	8.3	8.5	8.4	6.9	6.7	6.8
8	9.0	9.2	9.1	6.2	6.0	6.1
9	9.2	9.4	9.3	6.0	5.8	5.9
10	9.2	9.7	9.5	6.0	5.5	5.8
11	9.7	9.8	9.8	5.5	5.4	5.5
12	9.7	10.0	9.9	5.5	5.2	5.3
13	10.0	10.1	10.1	5.2	5.1	5.2
14	10.1	10.0	10.1	5.1	5.2	5.2
15	10.1	10.4	10.3	5.1	4.8	5.0
16	10.0	10.3	10.2	5.2	4.9	5.1
17	10.5	10.5	10.5	4.7	4.7	4.7
18	10.6	10.4	10.5	4.6	4.8	4.7
19	10.6	10.7	10.7	4.6	4.5	4.6
20	10.6	10.6	10.6	4.6	4.6	4.6
21	10.9	10.6	10.8	4.3	4.6	4.5
22	11.0	10.7	10.9	4.2	4.5	4.4
23	10.9	10.6	10.8	4.3	4.6	4.5
24	11.1	10.7	10.9	4.1	4.5	4.3
25	11.0	10.7	10.9	4.2	4.5	4.4
26	11.1	11.1	11.1	4.1	4.1	4.1
27	11.1	11.0	11.1	4.1	4.2	4.2
28	11.1	11.0	11.1	4.1	4.2	4.2
29	11.1	11.0	11.1	4.1	4.2	4.2
30	11.0	11.0	11.0	4.1	4.2	4.2
Average	9.5	9.5	9.5	5.7	5.7	5.7

The data obtained from a similar experiment on the same soil but with an initial moisture content of only 11.8 and exposed for shorter periods, 22 and 77 days, are reported in Table XII (3, p. 283). In this case no loss of water from the bottom of the soil column was shown during the first three weeks; but at the end of 11 weeks it amounted to 1 per cent, and the amount remaining in the lowest 18-inch portion of the column also averaged 10.7, the same as remained after the longer exposure of the more moist soil.

TABLE XII.—*Loss of water from a uniform soil, J, protected from all loss at the sides and below, but fully exposed to evaporation at the surface. All cylinders were filled on February 14 with soil containing 11.8 per cent of water*

Depth of section.	Water content on opening cylinder.				Loss of water.			
	March 7.		May 1.		In 22 days.		In 77 days.	
	Cylinder I (Surface mulched).	Cylinder II (Surface packed).	Cylinder III (Surface mulched).	Cylinder IV (Surface packed).	Cylinder I.	Cylinder II.	Cylinder III.	Cylinder IV.
Inches.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
1	3.0	3.3	2.2	2.2	8.8	8.5	9.6	9.6
2	4.4	6.5	2.2	2.4	7.4	5.3	9.6	9.4
3	7.4	8.2	3.8	4.6	4.4	3.6	8.0	7.2
4	8.8	8.6	5.6	6.2	3.0	3.2	6.2	5.6
5	9.1	9.1	6.8	7.4	2.7	2.7	5.0	4.4
6	9.5	9.4	7.4	7.8	2.3	2.4	4.4	4.0
7	9.5	10.0	7.8	8.8	2.3	1.8	4.0	3.0
8	9.7	10.1	8.1	8.6	2.1	1.7	3.7	3.2
9	9.9	10.1	8.3	8.9	1.9	1.7	3.5	2.9
10	10.1	10.3	9.0	9.1	1.7	1.5	2.8	2.7
11	10.3	10.5	9.1	9.4	1.5	1.3	2.8	2.4
12	10.4	10.6	9.2	9.5	1.4	1.2	2.6	2.3
13	10.6	10.8	9.7	9.5	1.5	1.0	2.1	2.3
14	10.9	10.9	10.0	9.8	1.5	.9	1.8	2.0
15	11.0	11.1	10.0	10.1	1.2	.7	1.8	1.7
16	11.2	11.2	9.9	10.0	.9	.6	1.9	1.8
17	11.0	11.4	9.8	9.9	.8	.4	2.0	1.9
18	11.1	11.4	9.9	9.9	.6	.4	1.9	1.9
19	11.1	11.4	10.0	10.7	.8	.4	1.8	1.1
20	11.1	11.4	10.0	10.6	.7	.4	1.8	1.2
21	11.2	11.4	10.1	10.2	.7	.4	1.7	1.2
22	11.4	11.4	10.2	10.3	.7	.4	1.7	1.6
23	11.4	11.4	10.4	10.3	.6	.4	1.6	1.5
24	11.5	11.4	10.5	10.4	.4	.4	1.4	1.5
25	11.4	11.4	10.6	10.7	.4	.4	1.3	1.4
26	11.5	11.5	10.7	10.8	.3	.3	1.2	1.1
27	11.4	11.5	10.7	10.7	.4	.3	1.1	1.0
28	11.5	11.5	10.9	10.7	.3	.3	1.1	1.1
29	11.5	11.6	10.9	10.8	.3	.2	.9	1.1
30	11.5	11.7	11.0	10.8	.3	.1	.9	1.0
31	11.5	11.7	11.0	11.0	.3	.1	.8	1.0
32	11.5	11.7	11.0	10.8	.3	.1	.8	1.0
33	11.5	11.8	11.0	10.8	.3	.0	.8	1.0
34	11.8	11.8	11.0	10.8	.0	.0	.8	1.0
35	11.8	11.8	11.0	10.8	.0	.0	.8	1.0
36	11.8	11.8	11.0	10.8	.0	.0	.8	1.0
Average	10.3	10.6	9.2	9.4	1.5	1.2	2.6	2.4

The movement from the portion of the subsoil below the twelfth inch evidently becomes exceedingly slow after the moisture content has fallen to a point approximately twice the hygroscopic coefficient. It should not be overlooked, however, that the point at which movement upward into the very dry surface has practically ceased is appreciably below that at which it occurred with the downward movement into the moist mass of the natural subsoil (Table XII), the ratio being 1.9 or 2.0 with the former and 2.4 with the latter. However, if even this close a concordance is found to hold in the field, the knowledge of the ratio would be very useful. Applying it, we should expect that a subsoil such as J with

a hygroscopic coefficient of 5.6 and situated in the second to the fifth foot below the surface would, after prolonged heavy rains, if protected from transpiration losses, as by clean fallowing, lose water by downward movement until it approached 14.0 per cent, while if exposed for six months to hot, rainless weather it would still carry not less than about 11 per cent, the available water then varying between approximately 8 and 5 per cent.

TABLE XIII.—*Loss of water from a uniform soil, D, protected from all loss at the sides and bottom, but fully exposed to evaporation at the surface. All of the cylinders were filled on September 2, No. I and II with soil containing 24.4 per cent and No. III and IV with soil containing 30.6 per cent of water. All were opened at the end of 78 days*

Depth of section.	Water content on opening cylinder.						Loss of water.	
	Cylinder I.	Cylinder II.	Average.	Cylinder III.	Cylinder IV.	Average.	Cylinder I-II.	Cylinder III-IV.
Inches.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
1	5.7	4.3	5.0	......	......	......	19.4	......
2	8.3	7.2	7.7	7.3	7.3	7.3	16.7	23.3
3	11.8	12.3	12.0	11.6	11.6	11.6	12.4	19.0
4	16.0	14.9	15.4	16.0	14.8	15.4	9.0	15.2
5	17.3	16.4	16.8	17.5	17.3	17.4	7.6	13.2
6	17.7	17.0	17.3	19.2	17.2	18.2	7.1	12.4
7	18.1	17.7	17.9	19.8	18.8	19.3	6.5	11.3
8	19.3	18.2	18.7	20.3	19.2	19.7	5.7	10.9
9	19.7	19.0	19.3	20.8	19.9	20.3	5.1	10.3
10	20.0	19.0	19.5	21.1	20.7	20.9	4.9	9.7
11	20.3	19.8	20.0	22.0	21.3	21.6	4.4	9.0
12	20.4	20.6	20.5	22.4	21.7	22.0	3.9	8.6
13	21.5	20.5	21.0	23.0	22.5	22.7	3.4	7.9
14	21.7	20.6	21.1	23.3	22.8	23.0	3.3	7.6
15	22.1	20.7	21.4	23.5	22.8	23.1	3.0	7.5
16	22.0	20.9	21.4	23.6	23.6	23.6	3.0	7.0
17	22.4	21.4	21.9	23.5	24.0	23.7	2.5	6.9
18	22.6	21.2	21.9	24.2	24.5	24.3	2.5	6.3
19	22.3	22.5	21.9	24.0	24.9	24.4	2.5	6.2
20	22.6	22.5	22.5	25.0	24.7	24.8	1.9	5.8
21	22.0	22.0	22.0	25.0	24.9	24.9	2.4	5.7
22	22.3	22.1	22.2	25.1	25.1	25.1	2.2	5.5
23	22.3	22.3	22.3	25.2	25.6	25.4	2.1	5.2
24	22.3	22.4	22.3	25.0	25.3	25.1	2.1	5.5
25	22.6	22.4	22.5	25.2	25.1	25.1	1.9	5.5
26	22.6	22.3	22.4	25.3	24.9	25.1	2.0	5.5
27	22.6	22.4	22.5	25.5	25.6	25.5	1.9	5.1
28	23.0	22.4	22.7	25.6	25.4	25.5	1.7	5.1
29	23.0	22.5	22.7	25.9	25.8	25.8	1.7	4.8
30	22.9	22.6	22.7	25.8	25.5	25.6	1.7	5.0
31	23.1	22.7	22.9	25.5	25.2	25.3	1.5	5.3
32	22.6	22.8	22.7	25.6	25.2	25.3	1.7	5.3
33	22.9	23.2	23.0	25.9	25.4	25.6	1.4	5.9
34	23.0	23.2	23.1	24.8	25.5	25.6	1.3	5.0
35	22.8	22.8	22.8	26.0	25.7	25.8	1.6	4.8
36	22.6	22.6	22.6	26.0	(a)	26.0	1.8	4.6
Average:								
1–3	8.6	7.9	8.2	9.4	9.4	9.4	16.2	21.1
1–6	12.8	12.0	12.4	14.3	13.6	13.9	12.0	16.6
1–9	14.8	14.1	14.4	16.6	15.8	16.2	9.9	14.4
1–12	16.2	15.5	15.8	18.0	17.2	17.6	8.6	12.9
13–24	22.2	21.5	21.8	24.2	24.2	24.2	2.6	6.4
25–36	22.8	22.6	22.7	25.6	25.4	25.5	1.7	5.1

[a] 26.0 used to obtain average.

A similar experiment was conducted with the silt-loam surface soil, D, which is rich in organic matter and has a hygroscopic coefficient of 10.2, and so is in sharp contrast with the residual subsoil J, practically devoid of organic matter and having a hygroscopic coefficient of only 5.6. The cylinders were similar to those used with J. Two, No. I and II, were filled with soil D, containing 24.4 per cent, and the others, No. III and IV, with the same soil, carrying 30.6 per cent of water. All were left with a compact surface for 11 weeks.

The losses of moisture in the former were confined chiefly to the surface foot, the final ratios in the second and third feet being 2.1 and 2.2, respectively, as compared with the initial ratio of 2.4. In the case of the two cylinders with the moister soil, with an initial ratio of 3.0, there was a distinct loss from all depths, the final ratio in the second and third feet being 2.4 and 2.5, respectively. The ratio in the upper half of a 12-inch column of this soil, to the surface of which in an air-dry condition 2 or 3 inches of water had been applied, after which it had been allowed to stand for 47 days, protected from evaporation, lay between 2.4 and 3.0 (Table X).

DISTRIBUTION OF MOISTURE WHEN EQUILIBRIUM HAS BEEN ATTAINED AFTER ADDING WATER TO THE SURFACE OF A COLUMN WHOSE MOISTURE CONTENT IS APPROXIMATELY EQUAL TO THE HYGROSCOPIC COEFFICIENT

In this experiment we used all 13 soils mentioned in Table I. In the case of each soil two galvanized-iron cylinders 2 feet long, 4 inches in diameter, and provided with bottoms and tight-fitting covers, were filled, as described above, with the soil having a moisture content approximately equal to the hygroscopic coefficient. To permit the escape of air as the water was being added, small holes had been made in the bottoms. The soil was tamped in until even with the rim, smoothed off, and covered with a metal tray, which was left on until all the cylinders had been filled.

In the case of each of the soils, except the dune sand Q, the initial water content was approximately equal to the hygroscopic coefficient and the amount of water added to the surface was sufficient to raise the average moisture content of all the soil in the cylinder to 1.5 times the hygroscopic coefficient, it varying according to the soil and the initial moisture content of this from 0.27 inch to 2.12 inches. To the sand Q, which was in an air-dry condition, the added water amounted to 0.5 inch in two cylinders and to 1.0 inch in two others.

To make more uniform the initial penetration of the water, the cylinders used were inverted in the flat-bottomed metal trays, the desired amount of water then added and allowed to rise into the soil by capillarity until all or nearly all had been absorbed, after which they were placed right side up. Where with the coarsest soils a few drops of water remained in the tray, these were added to the surface after the cylinder had

been inverted. Any soil adhering to the tray was transferred to the cylinder. The cover was then put on, and both the opening between this and the cylinder wall and the holes in the bottom were sealed with paraffin. The cylinders were weighed and transferred to a basement room in which the temperature was practically constant. There they were placed in a large box and covered to a depth of 8 inches with moist soil to prevent any sudden or extreme fluctuations in temperature and also any drying of the soil in the cylinders, if by any chance openings should develop, as, for example, by the cracking of the paraffin seal.

The cylinders were left undisturbed for 10 weeks, and most of them for 4 to 6 weeks longer. As soon as each was removed from the box, it was weighed, in order to determine whether there had been any change in weight during its stay in the box. In the case of none did the scales, sensitive to half an ounce, show any gain or loss. As the cylinders were removed from the box, moist soil was put in their place. All had been placed in the box on the same day, but in some instances not all of those removed at the same time could be opened on the same day. In such cases the unopened cylinders were left in the constant temperature room until such time as they were opened. Previous experiments with soil J had shown that after two months' standing the distribution of water was but little affected by leaving them longer undisturbed (3, p. 270).

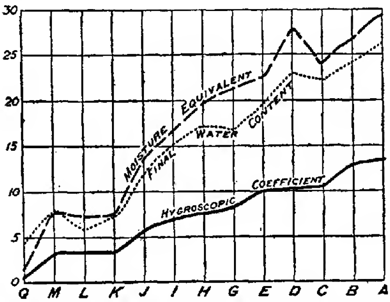

FIG. 2.—Diagram showing relationship between the final water content and both the hygroscopic coefficient and the moisture equivalent.

The distribution of the moisture at the end of this period for the 12 loams is given in Table XIV. That in the sand Q is treated separately. It will be seen that, except with B and G, the lower foot section had gained but little in moisture during the 69 to 110 days. Almost all the soils showed a very slight increase, even as far as the lowest portion of the cylinder; but only with B and G was this really distinct as deep as the twenty-first inch. The maximum depth affected in any case may be considered as the twenty-fourth inch. The final moisture content of the surface 3-inch section lay between 1.7 and 2.4 times the hygroscopic coefficient, the maximum in all cases being found in the surface inch. This relationship is shown in Table XV. Where the initial ratio was 1 or 1.1, the final ratio in the surface 3-inch section varied from 1.7 to 2.3, that in the lowest 3-inch section remaining as low as 1.1 to 1.2. Where

the initial ratio was as high as 1.3, the final ratio of the surface 3-inch section was similar to the above and that in the lowest section varied from 1.3 to 1.5.

The final moisture content of the surface layer in these loams bears an even closer relationship to the moisture equivalent than to the hygroscopic coefficient, being in general about nine-tenths of the latter value, the ratio varying from 0.80 to 1.01 (Table XVI and figure 2). As will be pointed out below, this is not the case with the sand Q and it would appear that with sands in general there would be a departure, increasing with the coarseness of the texture. However, the great majority of agricultural soils have a texture no coarser than that of K, L, or M.

TABLE XIV.—*Distribution of water in cylinders filled with soil containing a percentage of water approximately equal to the hydroscopic coefficient. To the surface of each enough water was applied to raise the total water content to one and a half times the hygroscopic coefficient, after which the cylinders were allowed to stand from 68 to 110 days*

Item.	Soil No.											
	A.	B.	C.	D.	E.	G.	H.	I.	J.	K.	L.	M.
Soil:												
Hygroscopic coefficient	13.3	12.9	10.5	10.2	10.1	8.2	7.6	7.1	5.6	3.4	3.4	3.3
Initial water..per cent	13.2	13.1	12.0	13.4	9.9	8.0	9.0	8.4	5.6	4.3	4.5	4.3
Initial ratio	1.0	1.0	1.1	1.3	1.0	1.0	1.2	1.2	1.0	1.3	1.3	1.3
Water applied..inches	2.11	2.12	1.21	.90	1.42	1.58	1.28	.60	.89	.33	.27	.33
Moisture equivalent	29.5	25.8	24.1	27.8	22.5	21.2	19.7	16.8	13.5	7.5	7.2	7.9
Time..days	110	69	100	110	100	106	102	102	70	100	68	100
Final water content (per cent):												
Depth—												
1 inch	27.5	25.5	23.4	24.1	20.5	17.4	18.0	16.3	12.2	7.8	6.2	8.7
2 inches	26.1	23.7	22.1	22.9	19.3	16.7	16.6	15.1	11.7	7.4	5.8	8.0
3 inches	25.1	23.5	21.2	21.6	19.0	16.3	16.7	14.0	11.3	7.1	5.5	7.3
4 inches	24.7	23.3	20.3	20.8	18.5	16.2	16.3	13.6	10.8	6.6	5.5	7.2
5 inches	24.3	22.9	20.2	20.2	18.6	16.0	15.9	13.6	10.5	6.4	5.4	6.6
6 inches	23.7	23.1	19.9	19.0	18.3	15.7	15.7	13.2	10.3	6.2	5.0	5.7
7 inches	22.9	23.1	19.4	18.0	18.0	15.6	15.5	12.7	10.0	5.9	5.1	5.0
8 inches	22.0	22.7	19.0	16.8	17.7	15.4	15.1	11.8	9.6	5.6	4.9	4.7
9 inches	20.8	22.4	18.1	15.9	16.9	15.0	14.8	10.8	9.5	5.3	4.6	4.7
10 inches	19.5	21.8	17.4	14.8	16.7	14.6	14.6	9.9	9.1	5.2	4.6	4.7
11 inches	17.6	21.4	16.8	14.0	16.2	14.4	14.2	9.5	8.6	5.0	4.3	4.6
12 inches	16.5	20.8	15.4	13.6	15.3	14.2	13.7	9.2	8.2	4.8	4.4	4.6
13 inches	15.3	20.4	14.5	13.4	14.8	14.0	13.2	8.9	7.5	4.7	4.2	4.7
14 inches	14.5	20.1	13.0	13.2	14.1	13.6	12.5	8.9	7.3	4.8	4.2	4.7
15 inches	14.0	19.6	12.9	13.1	13.2	13.3	12.3	8.8	6.6	4.6	4.1	4.7
16 inches	13.6	19.0	12.7	13.1	12.3	13.1	11.3	8.7	6.2	4.6	4.1	4.6
17 inches	13.5	18.3	12.4	13.1	11.7	12.9	10.7	8.7	6.0	4.6	4.2	4.7
18 inches	13.3	17.5	12.3	13.1	11.4	12.3	10.3	8.6	6.0	4.6	4.2	4.6
19 inches	13.2	16.9	12.4	13.1	11.0	11.8	9.6	8.7	5.7	4.6	4.4	4.7
20 inches	13.2	15.7	12.4	13.2	10.9	11.2	9.7	8.7	5.7	4.6	4.4	4.7
21 inches	13.1	15.0	12.4	13.2	10.8	10.7	9.7	8.7	5.7	4.7	4.4	4.8
22 inches	13.1	14.5	12.3	13.3	10.6	10.2	9.8	8.8	5.7	4.7	4.5	4.8
23 inches	13.0	14.5	12.2	13.2	10.5	9.9	9.7	8.8	5.9	4.7	4.4	4.8
24 inches	13.0	13.5	12.2	13.3	10.5	10.0	9.7	8.7	5.7	4.6	4.1	4.8
Average, 1 to 24 inches	18.1	19.9	16.0	15.9	14.8	13.8	13.1	10.6	8.2	5.4	4.7	5.3
Average, 1 to 12 inches	22.6	22.8	19.4	18.5	17.9	15.6	15.6	12.5	10.1	6.1	5.1	6.0
Average, 13 to 24 inches	13.6	17.1	12.6	13.2	11.8	11.9	10.7	8.7	6.2	4.7	4.3	4.7
Change in water content (per cent):												
1 to 12 inches	9.4	9.7	7.4	5.1	8.0	7.6	6.6	4.1	4.5	1.8	.6	1.7
13 to 24 inches	.4	4.0	.6	−.2	1.9	3.9	1.7	.3	.6	.4	.2	.4

TABLE XV.—*Ratio of final water content to the hygroscopic coefficient from 68 to 110 days after water had been applied to the surface of the soil column*

Soil.	Water added.	Initial ratio.	Final ratio.							
			1 to 3 inches.	4 to 6 inches.	7 to 9 inches.	10 to 12 inches.	13 to 15 inches.	16 to 18 inches.	19 to 21 inches.	22 to 24 inches.
	Inches.									
A	2.11	1.0	2.0	1.8	1.7	1.3	1.1	1.0	1.0	1.0
B	2.12	1.0	1.9	1.8	1.8	1.7	1.6	1.4	1.2	1.1
C	1.21	1.1	2.1	1.9	1.8	1.6	1.3	1.2	1.2	1.2
D	.90	1.3	2.2	2.0	1.7	1.4	1.3	1.3	1.3	1.3
E	1.42	1.0	1.9	1.8	1.8	1.6	1.4	1.2	1.1	1.0
G	1.58	1.0	2.0	2.0	1.9	1.7	1.7	1.6	1.4	1.2
H	1.28	1.2	2.3	2.1	2.0	1.9	1.6	1.4	1.3	1.3
I	.60	1.2	2.1	1.9	1.7	1.3	1.3	1.2	1.2	1.2
J	.89	1.0	2.1	1.9	1.7	1.5	1.3	1.1	1.0	1.0
K	.33	1.3	2.2	1.9	1.6	1.5	1.4	1.4	1.4	1.4
L	.27	1.3	1.7	1.6	1.4	1.3	1.2	1.2	1.3	1.3
M	.3	1.3	2.4	2.0	1.4	1.4	1.4	1.4	1.4	1.5

TABLE XVI.—*Ratio of final water content in the surface 3-inch section of loams to the moisture equivalent*

Soil No.	Final water content, 1 to 3 inches.	Moisture equivalent.	Ratio.	Soil No.	Final water content, 1 to 3 inches.	Moisture equivalent.	Ratio.
A	26.2	29.5	0.88	H	17.1	19.7	0.87
B	24.2	25.8	.94	I	15.1	16.8	.90
C	22.2	24.1	.92	J	11.7	13.5	.87
D	22.9	27.8	.82	K	7.4	7.5	1.00
E	19.6	22.5	.87	L	5.8	7.2	.86
G	16.8	21.2	.80	M	8.0	7.9	1.01

In the ratio of final water content to hygroscopic coefficient the extremes are shown by L, a subsoil, and M, the corresponding surface soil. The same soils also show almost the extremes in the ratio of final water content to moisture equivalent, in both cases the ratio being higher with M.

The conduct of the three soils K, L, and M, all from the same locality and similar in hygroscopicity, was striking, L retaining much less and M much more water than K. This behavior appeared so exceptional that the experiment with these was repeated two years later at the Minnesota Experiment Station, using duplicate cylinders in which soils K, L, and M had initial moisture contents of 4.4, 4.3, and 4.1 per cent, respectively. To each we added 0.33 inch of water, after which they were stored in a pit for 132 to 144 days. The resulting data are so nearly identical with those given in Table XIV that no purpose would be served by reporting them. This makes it certain that the differences between K, L, and M are not simply the result of unavoidable errors of experiment.

DISTRIBUTION OF MOISTURE WHEN EQUILIBRIUM HAS BEEN ATTAINED AFTER ADDING WATER TO THE BASE OF A COLUMN WHOSE MOISTURE CONTENT IS APPROXIMATELY EQUAL TO ITS HYGROSCOPIC COEFFICIENT

This experiment was similar to the preceding, except that the water was applied to the base of the column instead of to the surface. Similar cylinders were filled with the same soils, in the same manner, and at the same time, and were then placed upright in the small metal trays and the same amounts of water added as in the preceding experiment. The water was quickly absorbed through the small holes. The covers had been left off to permit the ready escape of the air expelled from the soil by the ascending water, the intention being to have these replaced as soon as the water had been absorbed, for which only a very short time was necessary, and then have both the opening between the cover and the cylinder wall and the holes in the bottom at once sealed with paraffin. Through a misunderstanding the covers were not placed on the cylinders, but all the latter being placed close together, each still resting in its tray, were covered with a large sheet of oilcloth and left in the basement room. Three days later, when the error was discovered, it was found that the oilcloth had been moved so that some of the cylinders were uncovered; but no one employed about the laboratory knew when the oilcloth had been disturbed or, accordingly, how long some of the cylinders had been exposed to evaporation. None had been weighed after being filled; but the weights of the empty cylinders, those of the different soils used, the initial moisture content, and the amount of the added water permitted a close calculation of what the weight of each should have been, provided no loss through evaporation had occurred. All the cylinders were at once covered and weighed. Those filled with soils A, D, and H had suffered the greatest loss, it having been, as closely as could be estimated, sufficient to lower the moisture content of a section of the soil column 6 to 8 inches deep by 2 or 3 per cent. As we decided to allow the cylinders to stand and determine the final moisture conditions, all were sealed and stored in the box of soil in the basement room and otherwise handled like those in the parallel experiment.

The duplicate cylinders of each of the loams showed a similar distribution of moisture; and, hence, only the averages are reported in Table XVII. In every cylinder the final moisture content of the uppermost section was found to be below the initial water content, the upward movement of water during the period of 74 to 115 days not having been sufficient to compensate for the loss into the still atmosphere in the darkened room during two and one-half days. This striking evidence of the extreme slowness of the upward movement of water under moisture conditions of the subsoil that resemble those met in dry-land fields with the water table far below that surface may possibly give the experiment an even greater value than it would have possessed had the misunderstanding not occurred.

TABLE XVII.—*Distribution of water in cylinders filled with soil containing a percentage of water approximately equal to the hygroscopic coefficient. To the bottom of each soil column enough water was added to raise the average water content to one and one-half times the hygroscopic coefficient, after which the cylinders were allowed to stand from 74 to 115 days*

Item.	Soil No.											
	A.	B.	C.	D.	E.	G.	H.	I.	J.	K.	L.	M.
Soil:												
Hygroscopic coefficient	13.3	12.9	10.5	10.2	10.1	8.2	7.6	7.1	5.6	3.4	3.4	3.3
Initial water, per cent [a]	13.2	13.1	12.0	13.4	9.9	8.0	9.0	8.4	5.6	4.3	4.5	4.3
Initial ratio	1.0	1.0	1.1	1.3	1.0	1.0	1.2	1.2	1.0	1.3	1.3	1.3
Water applied, inches	2.11	2.12	1.21	.90	1.42	1.58	1.28	.60	.89	.33	.27	.33
Moisture equivalent	29.5	25.8	24.1	27.8	22.5	21.2	19.7	16.8	13.5	7.5	7.2	7.9
Time ... days	115	74	107	115	107	107	107	107	107	107	73	107
Final water content (per cent):												
Depth—												
1 inch	10.9	12.6	9.9	9.8	8.0	8.0	7.5	6.5	4.7	3.7	3.1	2.9
2 inches	11.3	12.6	10.2	10.5	8.4	8.4	7.6	6.9	4.9	4.0	3.1	2.8
3 inches	11.7	13.5	10.3	11.1	8.9	8.9	8.0	7.3	5.1	4.1	3.1	3.6
4 inches	11.8	15.1	10.7	11.7	9.2	9.4	8.4	7.6	5.2	4.3	3.5	3.4
5 inches	12.1	16.6	11.4	12.1	9.6	10.4	8.9	7.8	5.3	4.4	3.5	3.6
6 inches	12.4	18.3	11.8	12.5	10.1	11.1	9.5	8.2	5.6	4.4	4.0	3.9
7 inches	12.6	18.9	12.2	12.5	10.7	11.5	10.0	8.4	5.7	4.3	3.9	4.1
8 inches	13.0	19.6	12.4	12.8	11.3	11.5	10.7	8.7	5.9	4.6	3.9	4.2
9 inches	13.3	20.1	12.8	12.9	12.5	13.1	11.5	8.7	6.5	4.7	3.9	4.4
10 inches	14.0	20.4	13.5	13.2	13.8	13.4	12.5	8.8	7.3	4.7	4.3	4.5
11 inches	15.1	20.7	14.9	13.4	14.6	13.9	13.1	9.0	7.9	5.0	4.3	4.4
12 inches	16.5	21.2	16.1	13.7	15.7	14.4	13.5	9.3	8.3	5.3	4.4	4.5
13 inches	18.2	21.9	17.0	14.5	16.2	14.8	14.2	9.7	8.9	5.2	4.5	4.6
14 inches	19.9	22.3	17.8	15.1	17.0	15.0	14.4	10.4	9.3	5.4	4.7	4.5
15 inches	21.2	22.9	18.8	16.2	17.2	15.5	15.0	11.4	9.9	5.6	4.9	4.8
16 inches	22.3	23.0	19.3	17.4	17.3	15.8	15.2	12.3	10.0	5.9	5.2	5.0
17 inches	23.3	23.3	19.7	18.8	18.0	16.3	15.7	12.9	10.2	6.3	5.7	5.7
18 inches	23.8	23.4	20.1	19.6	18.3	16.6	16.0	13.1	10.5	6.6	5.6	6.5
19 inches	24.2	23.7	20.5	20.8	18.8	17.0	16.4	14.0	10.3	6.9	5.8	7.0
20 inches	24.9	24.1	21.0	21.6	19.2	17.3	16.8	14.4	10.5	7.5	6.1	7.3
21 inches	25.3	24.0	21.1	22.4	19.4	17.3	17.1	14.6	10.7	7.4	5.9	8.1
22 inches	25.7	24.1	21.7	22.8	19.4	17.4	17.1	15.0	11.7	7.4	6.3	8.0
23 inches	25.9	24.1	21.8	23.5	19.6	17.5	17.1	15.0	11.9	7.4	6.4	8.2
24 inches	26.2	24.2	22.0	23.5	19.4	17.4	17.1	15.0	11.9	7.2	6.2	8.0
Average, 1 to 24 inches	18.2	20.4	16.1	16.0	14.7	13.8	13.0	10.6	8.3	5.5	4.7	5.2
Average, 1 to 12 inches	12.9	17.5	12.2	12.2	11.1	11.2	10.1	8.1	6.0	4.5	3.8	3.9
Average, 13 to 24 inches	23.4	23.4	20.1	19.7	18.3	16.5	16.0	13.2	10.5	6.6	5.6	6.5

[a] Some moisture was lost from the surface of the soil columns immediately after they were filled.

The distribution of moisture is just the reverse of that in the parallel experiment (Table XIV) with the same series of soils, the effect of the influence of gravity having disappeared during the prolonged exposure. The similarity is best shown by a comparison of the ratio of the final moisture content to the hygroscopic coefficient (Table XVIII), in which the data are so arranged as to facilitate comparison with those in Table XV. The similarity is striking, the soils which in the one show a low final ratio in the sections of the soil column nearest the point of application of the water showing a similar ratio in the other. The movement had been so alike in both experiments that the final distribution of the moisture appears independent of the direction through which the water had had to move, and we might regard the moisture conditions shown by either, aside from the dry sections in the latter experiment due to the error in procedure, to represent those for the particular soil, no matter what angle the axis of the column may make with the perpendicular.

TABLE XVIII.—*Ratio of final water content to the hygroscopic coefficient 74 to 115 days after water had been applied to the base of the soil column*

Soil No.	Water added.	Initial ratio.[a]	Final ratio of—							
			24 to 22 inches.	21 to 19 inches.	18 to 16 inches.	15 to 13 inches.	12 to 10 inches.	9 to 7 inches.	6 to 4 inches.	3 to 1 inches.
	Inches.									
A	2.11	1.0	2.0	1.9	1.8	1.5	1.1	1.0	0.9	0.8
B	2.12	1.0	1.9	1.9	1.8	1.7	1.6	1.5	1.3	1.0
C	1.21	1.1	2.1	2.0	1.9	1.7	1.4	1.2	1.1	1.0
D	.90	1.3	2.3	2.1	1.8	1.5	1.3	1.2	1.1	1.0
E	1.42	1.0	1.9	1.9	1.8	1.7	1.5	1.1	1.0	.8
G	1.58	1.0	2.1	2.1	2.0	1.8	1.7	1.6	1.3	1.0
H	1.28	1.2	2.2	2.2	2.1	1.9	1.7	1.4	1.2	1.0
I	.60	1.2	2.1	2.0	1.8	1.5	1.3	1.2	1.1	1.0
J	.89	1.0	2.1	1.9	1.8	1.7	1.4	1.1	.9	.9
K	.33	1.3	2.2	2.1	1.8	1.6	1.5	1.3	1.3	1.2
L	.27	1.3	1.9	1.7	1.6	1.4	1.3	1.2	1.1	.9
M	.33	1.3	2.4	2.2	1.7	1.4	1.4	1.3	1.1	1.0

[a] In the 1- to 3-inch section, and, in some of the soils, also in the next section, the initial moisture content was somewhat lower than this value.

The initial moisture content in the above parallel experiments is similar to that found in the subsoil traversed by the plant roots when the plants have just died or have begun to die from lack of moisture (2, p. 122). From these experiments it would appear safe to conclude that the water from any soil layer in which the ratio is not above 1.7 will not appreciably affect the moisture content of the soil at a distance of 12 inches or more, even during a period of three months. Even the maximum that remains in a subsoil in contact with the earth's soil mass after downward movement has ceased appears able to affect the moisture content to but a slightly greater distance during such a period. It would appear that with loam soils, such as those employed, the maximum ratio to be expected near the point of application, several months after the water had been added, would be between 1.6 and 2.5.

Under field conditions evaporation might prevent this ratio being found close to the surface, except for short periods following rain or irrigation, but at a distance of a foot or two it is to be expected, and, if not disturbed by the invasion of plant roots, may long persist.

When the ratio lies much below 1.0, the more moist soil seems to exert an influence upon the drier soil through a greater distance, which is to be attributed not to a movement of water along the surface of the soil grains but to evaporation of moisture into the air from the soil having a ratio in excess of 1.0 and its absorption from the resulting saturated atmosphere by the soil with a ratio below 1.0 (3, p. 259).

EXCEPTIONAL CONDUCT OF DUNE SAND

The distribution of water in coarse sands takes place quite differently from that in the loams above dealt with. Using the dune sand Q, with an initial content of 0.2 per cent of water, we added 0.50 inch in the case of five cylinders and 1.0 inch in the case of five others. All had been

filled and otherwise treated like those with the 12 loam soils, except that at the conclusion of the experiment the soil was removed in 3-inch instead of 1-inch sections (Table XIX). One cylinder of each group was opened at the end of 29, 63, and 78 days, respectively, while the remaining two were opened after 83 days. The distribution of moisture was very much the same at the end of 29 days as after 34 days more; but with the heavier application of water an appreciable downward movement took place between the sixty-third and the eighty-third day.

The 0.5 inch of water distinctly raised the moisture content of the sand to a depth of 6 inches and the 1-inch application to a depth of 12 to 15 inches. The surface 3-inch layer showed a final ratio of 8 to 10.

At the same time that water was added to the tops of the above 10 cylinders of dune sand it was applied to the base of the soil columns in two others filled at the same time, 0.5 inch to one and 1.0 inch to the other. At the end of 83 days both were opened. The moisture content of the five sections 1 to 12, 13 to 15, 16 to 18, 19 to 21, and 22 to 24 inches was 0.3, 0.5, 0.7, 4.4, and 7.1 per cent, respectively, in the former and 0.4, 0.5, 1.0, 5.6, and 12.1 per cent in the latter. In neither does the capillary movement seem to have extended beyond the ninth inch. The increase in moisture content in the higher sections is to be attributed to the movement of moisture through the soil atmosphere.

TABLE XIX.—*Distribution of water in cylinders filled with dune sand, they being allowed to stand from 29 to 83 days after 0.5 inch of water had been added to those in experiment A and 1.0 inch to those in B*

A.—0.5 INCH OF WATER ADDED

Depth of section.	Cylinder I (29 days).	Cylinder II (63 days).	Cylinder III (78 days).	Cylinder IV (83 days).	Cylinder V (83 days).	Average.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1–3	6.2	5.7	6.2	5.8	6.0	6.0
4–6	2.6	2.2	2.6	2.7	3.0	2.6
7–9	.4	.5	.5	.5	.5	.5
10–12	.2	.2	.4	.4	.4	.3
13–15	.2	.3	.5	.4	.4	.4
16–18	.2	.2	.3	.4	.4	.3
19–21	.2	.2	.4	.4	.3	.3
22–24	.2	.3	.3	.3	.4	.3
Average, 1–24	1.3	1.2	1.6	1.5	1.4	1.3
Average, 1–12	2.3	2.1	2.4	2.4	2.5	2.4
Average, 13–24	.2	.2	.4	.4	.4	.3

B.—1.0 INCH OF WATER ADDED

Depth of section.	Cylinder I (29 days).	Cylinder II (63 days).	Cylinder III (78 days).	Cylinder IV (83 days).	Cylinder V (83 days).	Average.
1–3	5.8	5.5	4.1	3.4	4.5	4.7
4–6	4.6	4.9	4.4	3.6	4.0	4.3
7–9	4.3	4.0	3.9	3.6	3.8	3.9
10–12	4.1	3.6	3.9	3.7	3.9	3.8
13–15	.6	.6	2.9	3.6	3.3	2.2
16–18	.6	.3	.7	1.5	.6	.7
19–21	.6	.4	.8	.5	.5	.6
22–24	.6	.3	.3	.4	.5	.4
Average, 1–24	2.6	2.4	2.6	2.5	2.7	2.6
Average, 1–12	4.7	4.5	4.1	3.6	4.1	4.1
Average, 13–24	.6	.4	1.2	1.5	1.2	1.0

The coarse sand exerts a retarding influence upon the movement of moisture through its own mass as well as upon that from overlying layers of finer texture.

The similarity in conduct of the soils with hygroscopic coefficients between 3.3 and 13.3 and the entirely different behavior of the sand with one of 0.6 make the conduct of the soils with values between 0.6 and 3.3 of great interest. As we included no representatives of these in the laboratory experiments, our conclusions in regard to them are based only upon field studies (p. 64).

RATIOS FOUND IN FIELD STUDIES

The published data on the total moisture content of soils of almost every degree of coarseness or fineness of texture, and determined under all kinds of weather, crop, and tillage conditions, are almost innumerable; but, as almost none of these are accompanied by statements of the hygroscopic coefficients of the samples or of any physical constants which would permit the calculation of these (8, p. 56; 6, p. 842; 4, p. 351), the data do not admit of testing the generalizations drawn from the above-described laboratory experiments. Occasionally an author has made such determinations on a few of the samples and then assumed that the subsoils were so uniform that these would apply to all. This assumption is correct in only exceptional places, and even then it should be first experimentally justified instead of the question being merely glossed over by the statement that the soils are characterized by great uniformity. For this reason we have to confine ourselves to our own field studies, carried out between 1907 and 1913 and as yet unpublished. All of these, we hope, will soon appear in another paper. As the determinations of the water content of each of the field samples was followed by one of the hygroscopic coefficient, the ratios are available in each case. In most instances the subsoil moisture had been more or less exhausted by plant roots and showed a ratio of between 1.0 and 1.5; such data are not of interest in the present study.

Our data on soils with hygroscopic coefficients lying between 3.0 and 14.0 are very numerous; those on the sands with a coefficient below 1.0 limited; and those on fine sands with coefficients between 3.0 and 1.1 very scanty. Of the first group we select only some worked out in the most detail.

It is scarcely permissible to compare the ratios of the final water content to the moisture equivalent, unless the latter value has been directly determined in the case of the samples in question, because the relation of this constant to the hygroscopic coefficient is quite variable (6, p. 845).

A.—Coarse sands.—Our data from field studies of the moisture in coarse sands are not numerous, but what we have are in accord with the results of the cylinder experiments. Table XX shows the conditions in the Nebraska sand hills in 1911 and 1912. Alternating hilltops and

basins, as well as scattered blow-outs, are characteristic features of this region. The last are almost bare of vegetation, and, hence, present conditions favorable to the subsoil carrying the maximum amount of water. The hilltops have a more scanty stand of plants than the basins; and, as a consequence, we should expect a smaller loss of water through transpiration and less likelihood of a low moisture content in the subsoil. All samples were composites from three borings, 10 to 30 feet apart.

The hygroscopic coefficient in all cases is low, 0.3 to 1.1. The moisture content, while low, was from 3 to 12 times the hygroscopic coefficient, the ratio in most cases lying between 4 and 8.

TABLE XX.—*Ratio of water content of Nebraska dune sands under natural conditions to the hygroscopic coefficient*

Depth.	Near Valentine, Aug. 21, 1911.			Near Thedford, Dec. 2, 1912.				Halsey Forest Reserve, Dec. 3, 1912.					
								Blow-out 1.		Blow-out 2.			
	Hill-top.	Ba-sin.	Blow-out.	Blow-out 1.	Blow-out 2.	Blow-out 3.	Blow-out 4.	Side.	Bot-tom.	Side.	Bot-tom.	Hill-top.	Ba-sin.
	PERCENTAGE OF TOTAL WATER												
Feet.													
1	4.6	4.4	6.5	4.7	5.3	4.0	4.1	3.1	3.1	2.7	2.4	2.9	3.3
2–3				4.6	7.5	3.2	4.3	2.9	3.7	2.9	3.4	2.9	4.0
4–5	4.5	2.7	6.1	6.0	10.0	6.6	6.0	3.3	4.1	2.9	3.2	2.6	4.1
6				6.5	8.5	6.6	8.0	2.9	4.1	3.1	2.7	1.7	3.7
	HYGROSCOPIC COEFFICIENT												
1	0.8	0.8	0.8	0.8	1.0	0.9	01.0	0.5	0.3	0.4	0.5	0.5	0.6
2–3				.8	1.0	1.0	1.0	.8	.4	.4	.5	.5	.6
4–5	.8	.9	.8	.8	.8	.9	1.1	.4	.4	.4	.6	.5	.7
6				1.0	.8	1.1	1.1	.4	.4	.4	.6	.4	.7
	RATIO OF TOTAL WATER TO HYGROSCOPIC COEFFICIENT												
1	5.7	5.5	8.1	5.9	5.3	4.4	4.1	6.2	10.3	6.7	4.8	5.8	5.5
2–3				5.7	7.5	3.2	4.3	3.6	9.2	7.2	6.8	5.8	6.7
4–5	5.6	3.0	7.6	7.5	12.5	7.3	5.5	8.2	10.2	7.2	5.3	5.2	6.9
6				6.5	10.6	6.0	7.3	7.2	10.2	7.8	4.5	4.2	5.3

A study in the abandoned Pope olive orchard, described by Mason (18, p. 17), 5 miles south of Palm Springs station, at the southern end of the Colorado Desert in California, furnished the data reported in Table XXI. After four months of hot, rainless weather, a rain, amounting, at the nearest United States Weather Bureau station, 5 miles north, to 1.90 inches, had fallen six days before the sampling. Pits adjacent to old trees were dug, exposing the subsoil below the lowest point to which the moisture from the recent rain had penetrated, and samples were taken from the walls of these pits.

The data show that the water had traveled downward only after raising the ratio to from 5 to 10.

It thus appears that, in the case of coarse sands, we may in general expect to find the water content as high as from 5 to 10 times the hygro-

scopic coefficient, unless it has been reduced by transpiration or evaporation. As capillarity in sands elevates water but a very short distance, the proportion of the rainfall available for transpiration by deep-rooted plants may be surprisingly large, as during the growing season the run-off is likely to be negligible, most of the water quickly penetrating beyond the influence of surface evaporation; and finally the further penetration to any great depth is much delayed, thus allowing time for its withdrawal by the roots.

TABLE XXI.—*Ratio of water content to hygroscopic coefficient in sandy soils and subsoil in an abandoned orchard near Palm Springs, Cal., on October 10, 1912*

Depth.	Pit I.	Pit II.	Pit III.
PERCENTAGE OF TOTAL WATER			
	Per cent.	*Per cent.*	*Per cent.*
1 to 12 inches	6.3	5.4	4.7
Second foot	8.6	6.0	4.9
Third foot	7.0	6.1	4.6
Fourth foot	6.4	.7	.7
Fifth foot	1.1	.7	1.3
HYGROSCOPIC COEFFICIENT			
2 to 12 inches	0.6	0.7	0.7
Second foot	.6	.7	.9
Third foot	.7	.7	.5
Fourth foot	.6	.7	.5
Fifth foot	.6	.6	.7
RATIO OF TOTAL WATER TO HYGROSCOPIC COEFFICIENT			
2 to 12 inches	10.5	7.7	6.7
Second foot	14.3	8.6	5.4
Third foot	10.0	8.7	9.2
Fourth foot	10.7	1.0	1.4
Fifth foot	1.8	1.2	1.9

B.—FINER-TEXTURED SOILS.—Data from a field study in the summer of 1912 permit a close comparison with the data from the laboratory experiments on soils A and D. A was a bulk composite from the fourth to fifth foot taken from an excavation being made for a new building on the Experiment Station grounds. Three hundred yards away a considerable area of subsoil had recently been exposed in preparing a railroad grade, 3 or 4 feet of surface material having been removed. Throughout the season we kept this exposed subsoil free of weeds, and at frequent intervals took samples for the determination of moisture in the different inch sections of the surface foot and less frequently in the foot sections to a depth of 6 feet. The samples employed in the case of the inch sections were from duplicate borings, 10 to 20 feet apart, using a soil auger 4 inches in diameter. D was a bulk sample of the surface 6 inches of soil taken from one side of a long cultivated field adjacent to the exposed

subsoil. This field was planted to corn in 1912; but an area 50 feet square, near the center of the field and less than 100 yards from both the exposed subsoil and the place where soil D had been collected, was kept free from all vegetation, but was cultivated the same as though it had been in corn. Moisture determinations parallel to those on the exposed subsoil were made here.

TABLE XXII.—*Hygroscopic coefficients, nitrogen, and organic carbon of the inch sections of surface foot in the areas near the Nebraska Experiment Station used for a detailed moisture study*

FALLOW FIELD

Depth.	Hygroscopic coefficient.					Nitrogen.	Organic carbon.
	Set I.	Set II.	Set III.	Set IV.	Average.		
Inches.						*Per ct.*	*Per ct.*
1	8.7	8.5	8.8	7.9	8.5	0.237	......
2	8.5	8.2	8.7	8.6	8.5	.235	......
3	8.5	8.9	9.3	9.0	8.9	.233	2.78
4	8.2	8.5	9.2	9.0	8.7	.233	......
5	8.5	8.7	8.7	9.2	8.8	.253	......
6	8.7	8.7	9.2	8.5	8.8	.251	......
7	8.8	9.4	9.3	8.0	8.9	.239	......
8	8.7	9.9	10.5	8.4	9.4	.211	2.27
9	9.3	9.6	10.5	9.2	9.7	.188	......
10	10.3	10.0	11.2	9.3	10.2	.171	......
11	11.1	10.5	11.6	9.8	10.8	.164	......
12	11.2	11.3	12.6	10.5	11.4	.154	1.86
Average, 1–6	8.5	8.6	9.0	8.7	8.7	......	......
Average, 7–12	9.9	10.1	11.0	9.2	10.1	......	......
Average, 1–12	9.2	9.4	10.0	9.0	9.4	.214	......

EXPOSED SUBSOIL

Depth.	Set I.	Set II.	Set III.	Set IV.	Average.	Nitrogen.	Organic carbon.
1	12.7	12.5	......	......	12.6	.047	......
2	12.7	12.6	......	......	12.6	.047	......
3	12.8	13.0	......	......	12.9	.045	0.25
4	13.2	13.2	......	......	13.2	.044	......
5	13.2	12.6	......	......	12.9	.044	......
6	13.2	12.5	......	......	12.9	.041	......
7	12.8	12.6	......	......	12.7	.040	......
8	12.7	12.6	......	......	12.7	.038	.18
9	12.7	12.7	......	......	12.7	.038	......
10	12.3	12.4	......	......	12.4	.038	......
11	12.4	12.7	......	......	12.6	.038	......
12	12.2	12.9	......	......	12.6	.036	.18
Average, 1–6	13.0	12.7	......	......	12.9	......	......
Average, 7–12	12.5	12.6	......	......	12.6	......	......
Average, 1–12	12.7	12.7	......	......	12.7	.041	......

Four sets of samples from this fallow area and two sets from the exposed subsoil, all taken for moisture determinations, were employed for the determination of the hygroscopic coefficient. The data from the different sets from the same field (Table XXII) are so similar for the corresponding soil layers of the surface foot that it appears permissible

to use the average values for all of the 12 inches in calculating the ratios. The nitrogen and organic carbon content reported in the same table show the typical character of the one as a surface soil and of the other as a subsoil. The average hygroscopic coefficient for the surface foot from the fallow field was 9.4 compared with 10.2 for the surface soil D, while that for the surface foot of the exposed subsoil is 12.7 compared with 13.3 for the subsoil A.

A Government rain gauge, maintained at the Experiment Station and within 400 yards of both sampled areas, furnished the data on the rainfall. The weather of the four months involved did not depart widely from the normal at Lincoln, except that the May rainfall, amounting to 0.69 inch occurring in five showers (0.10 inch on the 1st, 0.32 on the 4th, 0.15 on the 10th, 0.02 on the 20th and 0.10 on the 26th) was 3.64 inches below the normal. The rainfall for June, July, and August 1 to 26 amounted to 4.03, 2.68, and 3.86 inches, respectively. Both areas were sufficiently far from trees and alfalfa plants to avoid any draft by roots upon the subsoil moisture.

The compact, uncultivated, but weedless, and gently sloping surface of the exposed subsoil was unfavorable to the ready penetration of the rains and favorable to run-off, while the loose, almost level surface of the fallow field permitted ready penetration and prevented any serious lossby run-off.

The ratios for the surface inch and the four 3-inch sections are reported in Table XXIII. While on both areas the ratio in the surface 3-inch section fell very low during dry weather, at depths below this in the exposed subsoil it remained very constant, varying only from 1.9 to 2.4; but in the fallow it ranged from 2.1 to 3.9, the former after dry weather and the latter very soon after a heavy rain. In the fallow field the lowest 3-inch section showed a lower ratio than the overlying two sections, in this resembling the exposed subsoil.

Table XXIII.—*Ratio of water content to hygroscopic coefficient at different levels in the surface foot of two adjacent fields*

Date.	Weather conditions.	Bare subsoil.					Fallow field.				
		First inch.	1 to 3 inches.	4 to 6 inches.	7 to 9 inches.	10 to 12 inches.	First inch.	1 to 3 inches.	4 to 6 inches.	7 to 9 inches.	10 to 12 inches.
May 25-27	Prolonged hot dry weather followed by 0.10 inch rain	0.8	1.0	2.0	2.1	2.0	0.5	1.1	2.8	2.9	2.4
June 1	Within 8 hours after 0.50 inch rain	2.4	2.1	2.0	2.2	2.2	2.6	2.0	2.9	2.9	2.4
June 14	Within 5 hours after 2.71 inches rain	2.3	2.3	2.3	2.3	2.4	3.9	3.9	3.7	3.6	3.0
July 10	Prolonged hot dry weather followed by 0.24 inch rain	1.7	1.6	1.9	2.0	2.0	1.8	1.5	2.8	3.2	2.5
July 11	Within 4 hours after 0.81 inch	1.9	1.7	1.9	2.1	2.3	3.4	3.2	3.1	3.1	2.5
Aug. 3	After a week of dry weather	.9	1.3	2.0	2.1	2.2	2.7	2.5	2.1	3.1	2.5
Aug. 6	Within 6 hours after 1.30 inches rain	1.8	1.8	1.9	2.1	2.2	3.6	3.5	3.4	3.1	2.5
Aug. 16	Within 8 hours after 2.11 inches rain	2.1	2.1	2.1	2.2	2.1	4.0	4.0	3.9	3.4	2.7
Aug. 26	After 10 days of dry weather	1.2	1.7	2.0	2.0	2.1	1.7	2.3	3.1	3.0	2.5

Data on the first 5 feet of soil from the same two fields are available (Table XXIV). These are from samplings on June 19 and August 29, both sets of samples being composites from three borings. If we omit the first foot, the ratios for the different levels below the bare subsoil vary from 2.2 to 2.6, while with the fallow field they lie between 1.2 and 1.9. The lower ratios in the latter are clearly to be attributed, not to a lesser ability to retain moisture against seepage, but to the precipitation's not having been sufficient to raise the moisture content of the subsoil of the fallow to its upper limit after its having been reduced to a very low point by the crop on the field in 1911.

TABLE XXIV.—*Ratio of water content to hygroscopic coefficient at lower levels in the two fields mentioned in Table XXIII*

BARE SUBSOIL

	First foot.	Second foot.	Third foot.	Fourth foot.	Fifth foot.
Hygroscopic coefficient	12.2	12.2	12.2	11.8	12.0
Total water, June 19 ... per cent	26.9	28.9	29.6	29.1	31.2
Total water, August 29 ... do	24.8	26.8	27.4	28.7	29.2
Ratio, June 19	2.2	2.4	2.4	2.5	2.6
Ratio, August 29	2.0	2.2	2.2	2.4	2.4

FALLOW

	First foot.	Second foot.	Third foot.	Fourth foot.	Fifth foot.
Hygroscopic coefficient	10.6	14.7	13.5	13.0	13.0
Total water, June 19 ... per cent	28.1	17.8	21.7	24.2	24.5
Total water, August 29 ... do	23.9	27.2	23.8	22.1	23.5
Ratio, June 19	2.6	1.2	1.6	1.9	1.9
Ratio, August 29	2.3	1.8	1.8	1.7	1.8

In the case of the two fields just mentioned conditions were not such as to induce the maximum downward movement of the water contained in the surface foot, the underlying layers having a moisture content far above the hygroscopic coefficient. However, the data we obtained near McCook, Nebr., during the same summer, that of 1912, are strictly comparable with those obtained in the 2-foot cylinders, the moisture content of the underlying subsoil approximating the hygroscopic coefficient.

McCook, which is in the semiarid portion of Nebraska, had experienced a series of remarkably dry years. Between the middle of August, 1910, and the first of the following August there were only 6.36 inches of precipitation. During August there fell 4.34 inches, but this was followed by dry weather, so that by the advent of frost the moisture of the soil and subsoil had been reduced to approximately the hygroscopic coefficient. Two rains in the following March and two in

April, one of 0.55 inch on the 20th and the other of 1.38 on the 28th, moistened the surface. About a week after the latter date, on May 6 to 8, while the surface 6-inch section was still moist from the recent rain, samples to a depth of 6 feet were taken from nine fields near McCook. The hygroscopic coefficients and the ratios are reported in Table XXV. In the case of three prairie fields in which the moisture content of the subsoil had been reduced the previous season to practically the hygroscopic coefficient, the rains had raised the ratio of the whole of the first foot to 2.1 to 2.3, the upper half being the more moist; the second foot also had been affected, the ratio in it having been raised to 1.3 or 1.4. One field of wheat (winter) and one field that had borne corn the previous year and on which the stubble was still undisturbed showed similar moisture conditions; while the two other wheat fields and the remaining two with corn stubble, although showing similar moisture conditions on the surface, exhibit a higher ratio in the subsoil, as though the previous year's crops had not fully exhausted this of its moisture. If we compare the nine fields, we find the ratio in the surface foot to vary between 1.8 and 2.8.

TABLE XXV.—*Ratio of moisture content to hygroscopic coefficient in fields near McCook, Nebr., on May 6, 7, and 8, 1912*

HYGROSCOPIC COEFFICIENT

Depth.	Prairie fields.			Wheat fields.			Corn stubble.		
	I.	II.	III.	I.	II.	III.	I.	II.	III.
Feet.									
0 to ½	8.6	8.0	8.5	7.3	8.2	8.5	10.8	8.5	8.6
½ to 1	10.6	10.9	11.7	8.6	10.3	10.7	11.4	10.1	10.3
2	10.3	9.6	10.1	7.8	9.8	9.2	9.7	9.1	11.9
3	8.3	8.4	......	9.4	8.4	8.6	8.6	8.5	9.0
4	7.5	8.7	......	8.7	7.8	9.0	8.0	8.1	8.3
5	7.8	8.4	7.9	8.6	7.5	8.8	8.0	7.7	8.3
6	7.6	7.2	......	7.5	7.4	7.0	7.9	8.5	8.0

RATIO OF MOISTURE CONTENT TO HYGROSCOPIC COEFFICIENT

Depth.	Prairie fields. I.	Prairie fields. II.	Prairie fields. III.	Wheat fields. I.	Wheat fields. II.	Wheat fields. III.	Corn stubble. I.	Corn stubble. II.	Corn stubble. III.
0 to ½	2.3	2.5	2.3	2.8	2.5	2.1	1.8	1.8	2.2
½ to 1	2.0	2.2	2.0	2.6	2.1	2.0	1.9	1.9	2.1
2	1.4	1.4	1.3	2.0	1.6	1.2	1.4	2.1	1.5
3	1.1	1.0	(a)	1.1	1.5	1.3	1.0	1.6	1.2
4	1.0	1.0	(a)	1.1	1.4	1.3	1.1	1.2	1.2
5	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.2	1.1
6	1.1	1.3	(a)	1.3	1.2	1.2	1.1	1.1	1.2

[a] Samples lost.

No rain fell between April 28 and June 6; but between the latter date and June 18 there were nine rainy days, with a total precipitation of 2.77

inches. On June 26 and 27 we made an exhaustive study of the moisture conditions in a level field about 3 miles from the W. B. station. It had been plowed the previous autumn and had since been kept free of weeds, being planted to corn about June 1. At the time of our sampling, the corn plants, 8 to 10 inches high, in hills 3 feet 8 inches apart, were still too small to have made any considerable draft upon the soil moisture. Selecting a level portion of the field, one which would not be affected by run-off from higher land, or itself lose much water by run-off, we marked 25 sites for sampling, 10 yards apart from north to south and the same from east to west (fig. 3). Sites 1, 5, 21, and 25 were at the four corners and 13 at the center. These five were sampled to a depth of 6 feet with an auger. All the others were sampled to a depth of 4 feet, a tube being used on part of them. The moisture content and the hygroscopic coefficient were determined in the case of each member of the 25 sets. The moisture conditions were very similar in all. The moisture content of the second foot had been distinctly affected at each place, while in five (including Borings I and V in Table XXVI) that of more or less of the third foot also had been affected; but in none had that of the fourth foot been appreciably influenced. The data on the five 6-foot borings are given in Table XXVI. The ratio in the first two lies between 2.0 and 2.9, while in the fourth and fifth feet it is approximately 1.1. From a comparison of this table with the preceding it will be seen that in the seven weeks following the earlier sampling the moistened zone in the fields in clean cultivation appears to have extended downward about 1 foot.

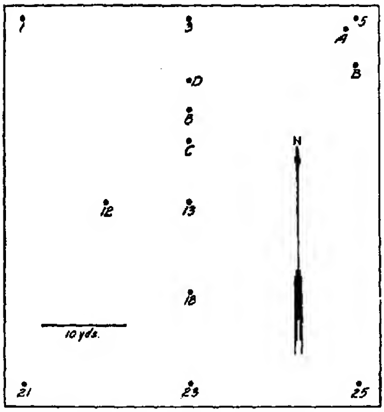

FIG. 3.—Diagram showing the relative location of sets of soil samples taken from field near McCook, Nebr.

To secure information as to how abrupt was the change in moisture content within a foot section in the case of seven borings, we separated into two parts the foot section that included the transition from moist to very dry soil. The upper section was the more or less moist portion,

possessing enough coherence to be removed from the boring by an ordinary soil auger, while the lower was the portion that was too dry and powdery to adhere to the ordinary auger and which had to be removed by a special auger carrying a sleeve. The data are reported in Table XXVII.

TABLE XXVI.—*Ratio of moisture content to hygroscopic coefficient in a clean cornfield near McCook, Nebr., on June 26 and 27, 1912*

HYGROSCOPIC COEFFICIENT

Depth.	Individual borings No. I.	II.	III.	IV.	V.	Average.
Feet.						
1	8.1	9.3	7.7	8.1	9.7	8.6
2	9.2	9.2	8.0	10.5	10.3	9.4
3	10.0	8.0	8.3	10.1	8.9	9.0
4	8.1	7.5	8.0	8.8	8.6	8.2
5	8.2	7.6	7.3	8.1	7.9	7.8
6	8.3	7.5	6.7	8.1	7.6	7.8
RATIO OF MOISTURE CONTENT TO HYGROSCOPIC COEFFICIENT						
1	2.6	2.6	2.9	2.7	2.4	2.6
2	2.2	2.1	2.0	2.1	1.8	2.0
3	1.3	1.1	1.0	1.0	1.6	1.2
4	1.1	1.2	1.0	1.0	1.1	1.1
5	1.1	1.1	1.0	1.1	1.1	1.1
6	1.2	1.2	1.4	1.1	1.2	1.2

TABLE XXVII.—*Comparison of the moisture conditions in the upper and lower part of the foot section that formed the transition from moist to very dry soil*

Boring No.	Depth.	Field notes.	Moisture.	Hygroscopic coefficient.	Ratio.
	Inches.		*Per cent.*		
1	25–28	Moist	17.0	10.0	1.7
	29–36	Dry	11.2	10.0	1.1
3	13–14	Moist	20.5	11.4	1.8
	15–24	Dry	15.1	10.0	1.5
8	13–21	Moist	20.3	11.5	1.8
	22–24	Dry	12.4	10.4	1.2
12	13–22	Moist	21.2	11.2	1.9
	23–24	Dry	14.7	[a] 11.2	1.3
18	13–21	Moist	18.7	10.7	1.7
	22–24	Dry	12.8	[a] 10.7	1.2
23	13–22	Moist	19.7	10.9	1.8
	23–24	Dry	12.8	[a] 10.9	1.2
25	13–18	Moist	15.9	8.9	1.8
	19–24	Dry	13.5	[a] 8.9	1.5

[a] The two portions of the foot section had been combined before the hygroscopic coefficient was determined.

The ratio in the moist upper portion of the foot section was 1.7, 1.8, or 1.9, while that in the dry "powdery" portion was distinctly lower—

1.1 to 1.5. The change in ratio here is even more abrupt than in the cylinders which had been allowed to reach equilibrium (Table XV).

In order to study the transition from moist to very dry soil in greater detail, sets of samples were taken with the inch sampler (previously described) in four different places in the same areas (fig. 3). In each set the sampled depth, including the whole of the moistened zone, extended from the surface well into the underlying dry zone. As will be seen from Table XXVIII, the samples were taken in such short sections as to make the results strictly comparable with those obtained with the cylinders. The ratio was found to fall within a short distance, 5 to 11 inches, from 2.0 to 1.1,—that is to say, from a condition not far from the optimum moisture content to one too dry to permit root development, and in which the soil is almost completely exhausted of available water, so far as ordinary crop plants are concerned. In set D, in which the transition was most gradual, this change required 16 inches. In each set the maximum ratio lay between 2.1 and 2.4, the maximum being somewhat lower than found in the first foot sections reported in Table XXVI.

TABLE XXVIII.—*Ratio of moisture content to hygroscopic coefficient at different distances from the surface in a clean cornfield near McCook, Nebr., on June 26 and 27, 1912*

Set A.			Set B.			Set C.			Set D.		
Depth of section.	Hygroscopic coefficient.	Ratio.	Depth of section.	Hygroscopic coefficient.	Ratio.	Depth of section.	Hygroscopic coefficient.	Ratio.	Depth of section.	Hygroscopic coefficient.	Ratio.
Inches.			*Inches.*			*Inches.*			*Inches.*		
1	8.0	0.4	1	7.8	0.4	1	7.4	0.7	1-3	8.8	1.9
2	8.3	1.9	2	8.3	1.4	2	8.0	1.8	4-6	11.3	2.1
3	9.3	2.3	3-4	9.8	2.4	3-4	8.7	2.4	7-9	11.6	2.1
4	.....	.....	5-6	10.7	2.2	5-6	9.8	2.3	10-12	11.5	1.8
5-6	9.5	2.3	7-8	11.5	2.1	7-8	10.5	2.2	13	10.7	1.8
7-8	10.9	2.0	9-10	11.4	2.1	9-10	12.2	1.9	14	10.4	1.8
9-10	12.5	1.9	11-12	11.6	1.9	11-12	11.1	2.0	15	10.4	1.8
11-12	11.7	2.0	13	11.1	1.9	13	11.1	1.9	16	.....	.....
13-14	12.1	1.7	14	10.4	2.0	14	10.6	2.0	17	10.8	1.7
15-16	11.2	1.7	15	10.4	1.9	15	10.5	1.8	18	10.7	1.6
17-18	10.2	1.6	16	9.4	2.0	16	10.6	1.7	19	9.8	1.8
19-20	9.9	1.1	17	9.4	2.0	17	10.5	1.5	20	10.3	1.6
21-22	9.9	1.0	18	9.1	2.0	18	10.5	1.2	21	10.3	1.5
23-24	9.6	1.0	19	9.2	2.0	19	10.6	1.1	22	9.7	1.5
25-26	9.3	1.0	20	9.2	2.0	20	10.6	1.0	23	9.7	1.4
27-28	9.1	1.0	21	9.1	2.0	21	10.6	.9	24	9.8	1.3
29-30	8.7	1.0	22	9.4	1.8	22	10.8	.9	25	9.4	1.2
31-32	8.1	1.0	23	9.2	1.9	23	10.1	.9	26	9.7	1.1
33-34	8.2	1.0	24	9.0	1.8	24	9.7	1.0	27	9.6	1.0
35-36	8.6	1.0	25	8.9	1.8	25	.....	.....	28	.....	.....
			26	9.0	1.6	26	9.7	.9	29	9.0	1.0
			27-28	9.0	1.3	27-28	9.7	1.0			
			29-30	8.6	1.1	29-30	9.3	.9			
			31-32	8.0	1.1	31-32	8.5	1.0			
			33-34	8.0	1.1	33-34	8.4	1.0			
			35-36	8.3	1.1	35-36	8.2	1.0			

C.—FINE SANDS.—Our field data on soils with hygroscopic coefficients between 1.1 and 3.0 such as fine sands, are very scanty and only where the samples were taken under conditions permitting an accumulation of moisture in the subsoil are they of interest in the present connection.

Under such conditions these soils show ratios between 3 and 5 (Table XXIX) and thus are intermediate between the coarse sands and the loams.

Table XXIX.—*Maximum ratios of water content to hygroscopic coefficient in Nebraska sandy soils*

Depth.	Near Madrid. Prairie, May 1, 1908.	Near Madrid. Prairie, Mar. 25, 1910.	Near Valentine. Corn, Aug. 21, 1911.	Near Valentine. Prairie, Aug. 21, 1911.	Near Imperial. Corn, stubble, May 11, 1912.	Near Imperial. Prairie, May 11, 1912.	Near Imperial. Prairie, May 11, 1912.
HYGROSCOPIC COEFFICIENT							
Feet.							
1	1.9	1.9	3.3	1.4	2.5	2.6	1.6
2	1.8	1.7	2.2	1.4	2.6	3.7	1.6
3	1.7	1.7	1.4	1.4	2.6	3.5	1.9
4	1.5	1.4	.9	1.2 (4–6 ft.)	3.0	3.5	1.5
5	1.8	1.4	.9		5.6	1.6	1.3
6	1.9	1.5	1.0		8.9	1.3	1.3
RATIO							
1	2.6	2.6	2.2	4.1	3.4	2.8	2.5
2	3.1	3.6	1.2	4.1	3.3	2.8	2.1
3	2.9	3.4	1.6	2.3	3.3	2.7	4.2
4	2.4	4.7	3.5	3.9 (4–6 ft.)	3.3	2.3	4.6
5	3.7	4.5	3.9		2.8	3.1	4.5
6	3.1	4.6	3.7		2.4	3.4	4.7

A later experiment in which several soils intermediate in texture were used along with those mentioned in Table I throws some light on the

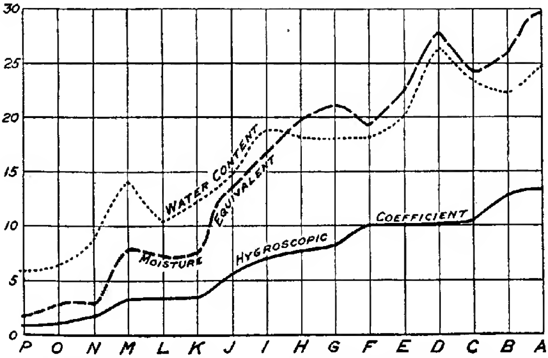

Fig. 4.—Diagram showing relation of water content of the surface section to both the hygroscopic coefficient and the moisture equivalent five days after 1 inch of water had been added to the surface of columns of dry soils.

conduct of these (Table XXX and figure 4). To the surface of columns of the soils containing an amount of water approximately half the hygroscopic

coefficient there was added 1 inch of water. The cylinders were allowed to stand protected from evaporation for five days, and then the moisture content of the upper 2 or 3 inches of moistened soil determined.

TABLE XXX.—*Ratio of moisture content to hygroscopic coefficient in the surface section five days after 1 inch of water had been added to the surface of the column of dry soil*

Soil No.	Hygroscopic coefficient.	Initial moisture content.	Moisture content.	Ratio.
		Per cent.	*Per cent.*	
A	13.3	6.6	24.6	1.9
B	12.9	6.3	22.2	1.7
C	10.5	5.0	23.3	2.2
D	10.2	4.9	26.4	2.6
E	10.1	5.0	20.1	2.0
F	10.0	4.8	18.0	1.8
G	8.2	3.9	18.0	2.2
H	7.6	3.8	18.0	2.4
I	7.1	3.5	18.8	2.6
J	5.6	2.8	14.6	2.6
K	3.4	1.7	12.3	3.6
L	3.4	1.6	10.5	3.1
M	3.3	1.7	14.1	4.3
N	1.7	.6	8.8	5.2
O	1.1	.4	6.4	6.6
P	.9	.2	5.9	6.6
Q	.6	.2	9.0	15.0

The retardation of movement appears to increase with the decrease in the coefficient when this is below 2.0; and even with K, L, and M, with coefficients between 3.0 and 4.0, a retardation is apparent during the first five days following the application of water, although, as shown above, this was not observable after the lapse of two months.

RÔLE OF THE MOISTURE OF THE DEEP SUBSOIL

From the above statements it would appear that a definite answer may be given to the question as to how far the water in the deeper subsoil is of importance to annual crop plants. As the minimum to which crops can reduce the moisture in the upper subsoil—that traversed by the roots—is approximately 1.0 to 1.1 times the hygroscopic coefficient; and, as the maximum to be expected in the deeper subsoil is 1.7 to 2.5 in the case of loams, it becomes a question of how far and how rapidly the moisture in a layer in which the ratio is 2.5 will move upward into an overlying layer with a lower ratio of, say, 1.0 to 1.1. The experiments have shown that equilibrium may be practically attained when these extremes are to be found as close together as 2 feet, or even less, and that the movement is so limited that three months was insufficient to restore, by upward capillary movement, the small amount of moisture lost during 2½ days into the still air of a basement room from the surface of soils with a ratio of 1.0. While a very much higher ratio is encountered

in coarse sands when the downward movement has become so slight as to be almost negligible, the upward movement in these is limited to very short distances. From these considerations it is evident that the amount of water which the deep subsoil can contribute to the growth of annual-crop plants will be of no practical importance. When a perennial crop with a root range of 20 to 30 feet follows an annual with one of only 4 to 6 feet, the moisture of the deeper subsoil becomes of great importance; but here it is a case of the roots going to the moisture and not of this being elevated to them by capillarity.

The experiments described, however, do not answer the question as to whether the moisture of the deeper subsoil may not, in the course of several years, or of a few decades, be elevated through a much greater distance. For instance, whether after the subsoil to a depth of 20 or 30 feet has been exhausted of available moisture (brought to a ratio of 1.0 to 1.1) by deep-rooted perennials, it may not eventually have the ratio restored to 1.7 to 2.4 by capillary movement from the deeper subsoil instead of only by the portion of the precipitation reaching it from above. Even if a decade were required for such a transfer, the elevated moisture might still have some practical importance for the perennial crops. Field investigations and laboratory experiments which would definitely decide this point appear simple in principle. The character of suitable cylinder experiments will be evident from those discussed above. For these the calcareous loessial silt loams of the Great Plains, and the so-called "volcanic ash" of eastern Washington and Oregon would be especially suitable.

A field study, if sufficiently thorough, would give a more satisfactory answer, but it would be far more laborious, and in most places would appear to be quite impracticable. It should necessarily be conducted in a region of limited rainfall, and even there a wet year or two might cause the experiment to miscarry entirely. Desirable conditions would include a silt-loam subsoil comparatively uniform to a depth of 40 feet, free of any interrupting sand or gravel layers, and a water table at a depth of not less than 100 feet. The subsoil of the field practically exhausted of available moisture to a depth of 20 or 30 feet, as by a long continued stand of alfalfa, should be sampled at intervals of a foot or so from the surface through the dry zone and well into the moist deeper subsoil. The places of sampling should be sufficiently numerous to establish the uniformity of the distribution of moisture; and with all samples there should be a determination of the hygroscopic coefficient or moisture equivalent, as well as of the total moisture. In beginning the study the perennial crop on the experimental field should be at once killed to prevent further loss by transpiration, and only annuals should be allowed on it during the experiment. The thickness of stand and the period of growth of these annuals should be such as to intercept most

completely the precipitation. The deep samplings for moisture determinations should be sufficiently numerous, frequent, and deep to afford a reliable history of the moisture content in the moist lower subsoil, in the central dry zone, and in the intermittently moistened surface layer. To illustrate the difficulty of securing a satisfactory site for such a field study, it might be mentioned that in no part of Minnesota would it appear feasible, either the climate being too humid, the water table too near the surface, or, lastly, the subsoil being too shallow where free of rock fragments and, where deep enough, carrying too many such fragments to permit satisfactory sampling.

SUMMARY

Uniform columns of soil of known hygroscopic coefficient and moisture equivalent were employed in various laboratory experiments, the 13 soils used ranging in texture from a coarse sand to a silt loam with hygroscopic coefficients of 0.6 and 13.3, respectively.

Five of the loams, placed in capillary connection with the natural subsoil mass, saturated with water and allowed to stand protected from surface evaporation for several months, lost water until the amount retained bore a close relation to the hygroscopic coefficient, being from 2.1 to 3.1 times this value, according to the particular soil. When a layer of coarse sand or gravel separated the column of loam from the natural subsoil mass or interrupted it, the downward movement of the water in the soil above this layer was much delayed. Where the column consisted of successive 2-inch layers of loams differing widely in texture, the order of their arrangement exerted no influence upon their final water content.

Soil columns 30 to 36 inches long, while protected from all loss of of moisture at the sides and bottom, were freely exposed to evaporation at the surface for periods varying from a few weeks to half a year. The moisture content, originally uniform and lying between 2.0 and 3.0 times the hygroscopic coefficient, fell until it reached, at depths below the first foot, an almost constant minimum with the ratio 1.9 to 2.2.

Employing 2-foot columns of 12 different loams, each with an initial moisture content approximately equal to its hygroscopic coefficient, enough water was added to raise the average moisture content of the column to 1.5 times the hygroscopic coefficient, the water being applied in one experiment to the top and in another to the base of the column. After the cylinders had stood for three or four months fully protected from evaporation the distribution of moisture, with regard to the surface to which it had been applied, was found to be the same in both experiments. The maximum distance through which an effect was shown was about 2 feet, but in most cases much less. The maximum final ratio of moisture content to hygroscopic coefficient was found in

the section adjacent to the surface of application, where it lay between 1.7 and 2.4. The ratio, while falling within these limits, is not a constant, it not being the same for all the soils that have the same hygroscopic coefficient.

The water-retaining capacity of the loams, as determined by laboratory experiments, was found to bear a somewhat closer relation to the moisture equivalent than to the hygroscopic coefficient, the ratio varying between 0.8 and 1.2.

Coarse sands exhibited a behavior very different from that of the loams. The ratio in the surface 6-inch section, even three months after 1 inch of water had been applied to the surface, was as high as 6.0 or 7.0, while in the second foot it was only 1.0. The field studies on coarse sands showed as high a final ratio as was observed in the laboratory experiments.

The very limited studies on fine sands indicate that these occupy a position intermediate between the loams and the coarse sands, the ratio of the water-retaining capacity to the hygroscopic coefficient rising as the latter value falls.

Field studies show that when loams, after rains sufficiently heavy to moisten them thoroughly, are protected from losses by evaporation and transpiration, they lose water by downward movement until the ratio of moisture content to hygroscopic coefficient lies between 1.8 and about 2.5, and accordingly on the uplands of dry-land regions this is the ratio to be expected in the deeper subsoil—the portion below the range of plant roots.

A comparatively abrupt transition from the moistened soil to the thoroughly exhausted underlying layers, with ratios of 2 to 2.5 and 1.0 to 1.1, respectively, is found even several months after liberal rains have fallen, if the subsoil to a considerable depth had previously been exhausted of available water.

The moisture of the deeper subsoil will be able to move upward only so slowly and through such a short distance in a single season that it will be at most of no practical benefit to annual crops. To make use of any portion of the precipitation which penetrates beyond the reach of the roots of annual crops it will be necessary to follow such crops at intervals by deep-rooting perennials.

Further experiments of a long-time character are necessary to decide definitely whether the deep subsoil may not in a decade or so contribute sufficient moisture to the subsoil within the reach of the roots of such perennials, 20 to 30 feet, to make such a contribution of some practical importance for such crops.

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